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Unequal Attention Allocation in Multiple Object Tracking

Unequal Attention Allocation in Multiple Object Tracking

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Abstract

Tracking multiple objects as they move around the environment is a crucial everyday skill. This thesis investigated whether attention can be split unequally between moving objects to determine the nature of the attentional resource that underlies tracking. Fixed architectural models argue that a limited number of slots support tracking whereas flexible models propose a continuous pool of resources. A modified MOT task was developed which required participants to split their attention unequally between moving objects. Under both theories, unequal attention splitting is theoretically possible. However, each theory predicts a different pattern of results in an unequal attention splitting paradigm. Under a fixed account, a stepped increase in performance as target importance increases is predicted whereas, under a flexible account, a graded increase in performance is predicted. Chapters 2 and 3 showed that participants could split attention unequally in response to target priority and reward. Across four experiments, there were mixed results regarding the nature (i.e. stepped or graded) of the increase in performance as target importance increases. Therefore, hybrid models of MOT need to be developed which combine components of both fixed and flexible theories. Chapter 4 found no evidence for attentional narrowing under conditions of anxiety but further demonstrated unequal attention splitting. The overarching conclusion of this thesis is that unequal attention splitting is possible, indicating some flexibility to the attentional resource. Further research using the unequal attention splitting paradigm has the potential to distinguish theories of multiple object tracking.

Dedication

For my Granny, Dorothy Crowe. You were such an amazing Granny and so incredibly strong. Thank you for being such a big part of my life and for all the very special memories!

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I am hugely grateful to Dr Chris Kent for your consistent support throughout my PhD. Thank you for saying yes and engaging in all my random ideas that fell far outside the remit of my PhD but made it an even more enjoyable three years. Thank you to Dr Angela Attwood for your expertise and guidance which has helped my development to becoming a truly rigorous researcher. I am extremely thankful to Dr Christina Howard for being an invaluable addition to my PhD. You have an incredible ability to make the most complex ideas make complete sense and I've thoroughly enjoyed all our conference trips. I would also like to thank Professor Alex Holcombe and Dr Sam Vine for welcoming me into your labs and being incredible hosts on my study visits. Thanks also go to Professor Iain Gilchrist for many helpful discussions along the way and Dr Ed Morris for all the MATLAB help. I am grateful to the University of Bristol for providing funding for my PhD and to all the students who participated in my experiments. A special thank you goes to Maria Antoniou, Veronika Hadjipanayi, India Derrick, Hannah Cook, Megan Manuel and Grace Lakey for their assistance with data collection.

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Author’s Declaration

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's *Regulations and Code of Practice for Research Degree Programmes* and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: ________________________ DATE: 01/03/19

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Chapter 1 Introduction

1.1 Thesis Overview

This thesis aims to distinguish between fixed and flexible theories of multiple object tracking (MOT). Fixed theories argue that a limited number of slots underlie tracking whereas flexible theories propose a continuous resource. An unequal attention-splitting MOT task was developed to investigate whether participants can prioritise one target relative to another and, therefore, split attention unequally. As target importance increases, fixed and flexible theories predict a stepped and graded increase in performance, respectively. Eight experiments manipulated target priority and reward to investigate their effect of tracking performance. The pattern of results from these experiments provides insight into the debate regarding the structure of the attentional resource that underlies tracking.

1.2 Overview of Multiple Object Tracking

Many everyday tasks require us to track multiple spatially distinct objects as they move around the environment. For example, drivers track the surrounding vehicles, cyclists and pedestrians to avoid any collisions and athletes might track the ball, their team mates and their opposition to successfully execute an interception. Occupations such as CCTV monitoring and air traffic control also utilise this skill. It is unsurprising, therefore, that there is a large amount of research aimed at understanding our ability to track multiple moving objects.

The multiple object tracking (MOT) paradigm, first developed by Pylyshyn and Storm (1988), has been used extensively to investigate MOT in a laboratory setting. In a typical MOT task, several objects are presented on screen, a subset of which are identified as targets by either a colour change or temporary flashing. The targets then return to being visually identical to distractors and participants are instructed to track the targets as they move around the screen for several seconds (or minutes, see Wolfe, Place, & Horowitz, 2007). At the end of a trial, all objects stop moving and one of four response procedures have typically been used to index tracking performance (see Hulleman, 2005, for a review). Mark-all (i.e. "select all the targets") and Probe-one (i.e. "was this object a target?") query participants about the status of an object (i.e. target or distractor). Trajectory- and position-tracking tasks require participants to report on the final trajectory and position of a queried target, respectively.

1.3 Factors Affecting MOT

It is well documented that manipulating task parameters affects tracking performance. Franconeri, Jonathan, and Scimeca (2010) suggest that the three primary factors influencing tracking are target speed, target number and inter-object spacing. Research has shown a decrease in tracking accuracy when participants must track more targets (Pylyshyn & Storm, 1988; Yantis, 1992), with early research leading to the proposal of a four-item limit for tracking (e.g. Intriligator & Cavanagh, 2001; Pylyshyn & Storm, 1988; Scholl, Pylyshyn, & Feldman, 2001). Poorer tracking performance is also revealed when the speed of the targets increases (e.g. Alvarez & Franconeri, 2007; Tombu & Seiffert, 2008) and when inter-object spacing decreases (e.g. Alvarez & Franconeri, 2007; Franconeri, Lin, Pylyshyn, Fisher, & Enns, 2008; Tombu & Seiffert, 2008). Franconeri and colleagues (2007; 2008; 2010) argued that the primary constraint on performance is inter-object spacing because the speed limit for tracking an unlimited number of objects is the same as the speed limit for tracking one object when spacing is held constant. This argument was further supported by research showing that overlapping objects, through them expanding and contracting, increases crowding which leads to a decrease in tracking performance (Howe, Holcombe, Lapierre, & Cropper, 2013; Van Marle & Scholl, 2003).

Other variables have also been identified as affecting tracking accuracy. Tracking performance is better when there are fewer distractors (Bettencourt & Somers, 2009; Sears & Pylyshyn, 2000) and when there is greater distinctiveness (i.e. fewer shared features) between targets and distractors and, therefore, less interference (e.g. Feria, 2012; Makovski & Jiang, 2009). Alvarez and Cavanagh (2005) showed that tracking capacity is independently constrained to the left and right hemifields because twice as many targets could be successfully tracked when they were divided between the left and right hemifields compared to when they were all presented in the same hemifields, a result supported by Hudson, Howe, and Little (2012) in a multiple identity tracking (MIT) paradigm, in which information about both spatial location of an object is required (although it was not as strong). Meyerhoff, Papenmeier, Jahn, and Huff (2013) showed that changes in the direction of targets impair tracking performance, with Howe and Holcombe (2012) revealing evidence that tracking performance was better when objects moved in predictable, compared with random motion paths. Luu and Howe (2015) also showed that when objects moved along linear paths, performance was better than when objects randomly changed direction every 300-600ms.

1.4 Cognitive Processes in MOT

Multiple Object Tracking is an attentionally demanding task. Pylyshyn (2006) used a dual-task set up in which participants performed a MOT and probe detection task simultaneously. In the probe detection task, participants had to respond as quickly as possible when they detected a probe on the computer screen. A larger percentage of probes were detected when they were presented on a target, indicating that attention was allocated towards these locations (Pylyshyn, 2006). The same pattern of results has been found in subsequent research (Huff, Papenmeier, & Zacks, 2012; Pylyshyn, 2006; Pylyshyn, Haladjian, King, & Reilly, 2008; Sears & Pylyshyn, 2000). Pylyshyn (2006) also found evidence that distractors were inhibited during tracking because detection rates were higher when the probe appeared in an empty background compared with on a distractor (Pylyshyn, 2006). This further implicates an attentional component to tracking, with attention-related inhibition proposed to be a top-down, goal-directed process (Watson & Humphreys, 1997; Braithwaite, Humphreys, & Hodsoll, 2003). Using a dual task set up, Tombu and Seiffert (2008) showed that MOT performance interfered with a tone discrimination task and Kunar, Carter, Cohen, and Horowitz (2008) showed that MOT performance was disrupted when performed concurrently with a telephone conversation. These dual-task studies clearly highlight the attentional demands of MOT. In addition, Huang, Mo and Li (2012) explored the interrelations between multiple visual attention paradigms to assess whether they were measuring the same underlying construct. Although MOT did not correlate with all other paradigms, it was correlated with a general factor of visual attention. Since the main features of the MOT task closely match attentional demands of real-world tracking, this task can be used to better understand the basic principles of visual attention.

Tracking also requires a visual selection component in which participants must correctly mentally *tag* targets at the start of a trial. Ma and Flombaum (2013) showed that errors in MOT arise due to uncertainty about the number of targets at the start of a trial which implicates visual selection as being a crucial part of tracking. Wolfe, Place, and Horowitz (2007) introduced the notion of multiple object juggling because it is rare that target objects are identified simultaneously and remain constant over time. Participants were able to *juggle* multiple objects, namely they could select and then drop targets within a trial demonstrating a role of selection within a trial, as well as at the start of a trial. Neurophysiological evidence from research using event-related potentials (ERPs) also supports a distinction between selection and tracking (Drew & Vogel, 2008). The N2pc component reflects the selection of targets amongst distractors and the CDA component reflects sustained attention during tracking (Drew & Vogel, 2008).

In MOT tasks, participants must both continuously monitor the changing spatial locations of targets (i.e. tracking) and actively maintain target representations over time which requires visual working memory (VWM), another process involved in MOT. Drew, Horowitz, Wolfe, and Vogel (2011) revealed neural activity that indicates two separate mechanisms are involved in tracking: an indexing mechanism that is closely tied to VWM and a mechanism that tracks target locations. Oksama and Hyönä (2004) explored individual differences in MOT performance and revealed that visuospatial short-term memory capacity was a significant predictor of MOT, highlighting a role for memory within tracking. The well-documented finding that participants can track objects through occlusion (e.g. Flombaum, Scholl & Pylyshyn, 2008; Horowitz, Birnkrant, Fencsik, Tran, & Wolfe, 2006; Scholl & Pylyshn,

1999) also implicates memory within a MOT framework. More specifically, Horowitz et al. (2006) suggest that participants can tolerate such gaps in tracking by using memory to store the object's characteristic when it disappears and retrieve such memories when the object reappears. Fougnie and Marois (2009) showed that a tracking task disrupted feature binding in VWM which suggests a dual-task cost and role of VWM in tracking (although see Fougnie & Marois, 2006, for earlier conflicting evidence). Meanwhile, Green and Bavelier (2006) reported that video-game players were able to track more objects which they proposed was due to changes in VWM capacity. This finding fits with training studies that have shown that an increase in VWM capacity is associated with improved MOT performance (Vartanian, Coady, & Blackler, 2016). Together, such research suggests a role of VWM in MOT.

1.5 Theories of MOT

The well-documented limits on performance (e.g. speed, spacing, target number) indicate that there is a finite attentional resource available to support tracking. Specifically, by increasing the difficulty of a MOT task, the attentional resource can be exhausted to the extent that a second object cannot be tracked (Holcombe & Chen, 2012). The structure of this resource is debated, with two competing theoretical frameworks. Fixed theorists propose a fixed architectural system consisting of a limited number of discrete pointers or slots (e.g. Pylyshyn, 1989), whereas flexible theorists argue for a continuous pool of resources (e.g. Alvarez & Franconeri, 2007). Figure 1.1 shows a schematic diagram for the main theories of MOT, which are outlined below.

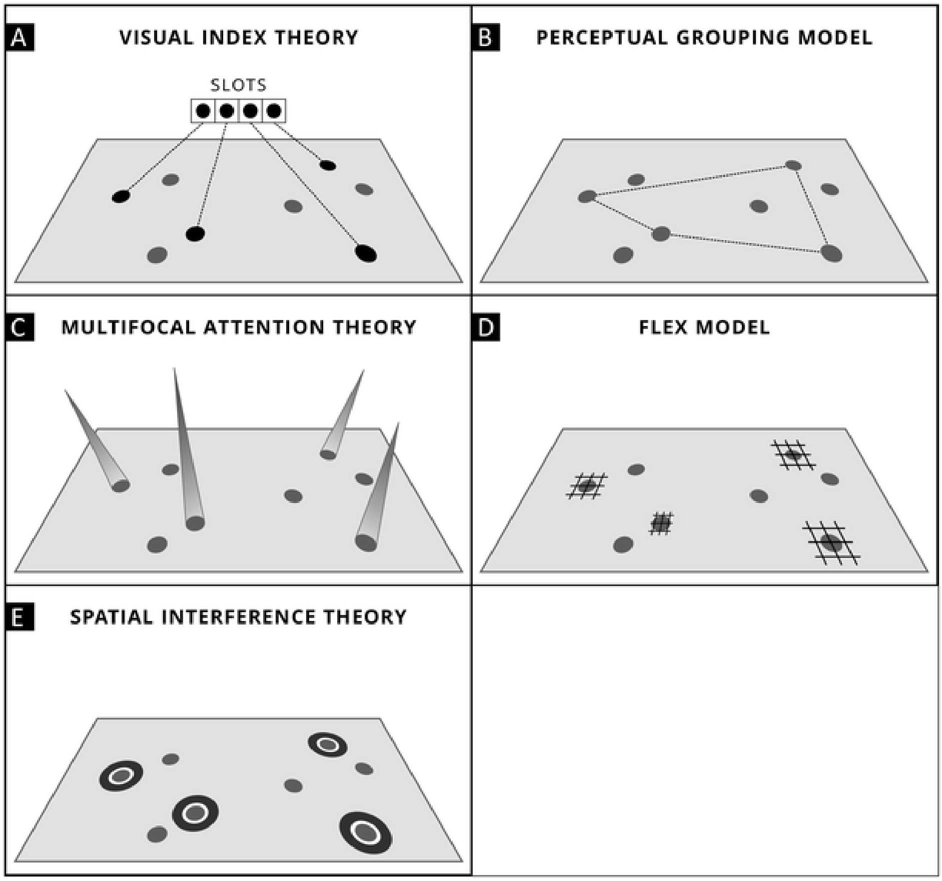


Figure 1.1. Schematic diagram of the main theories of MOT. Panels A, B and C represent fixed theories and Panels D and E represent flexible theories. Reprinted from "Studying visual attention using the multiple object tracking paradigm: a tutorial review", by H. S. Meyerhoff, F. Papenmeier, and M. Huff, 2017. *Attention, Perception, and Psychophysics,* 79, 1255. Copyright 2017 by Springer.

1.5.1 Fixed Theories of MOT

Fixed theories emerged following the consistent finding that approximately four targets could be accurately tracked in MOT tasks (e.g. Intriligator & Cavanagh, 2001; Pylyshyn & Storm, 1988; Scholl, Pylyshyn & Feldman, 2001). Pylyshyn's (1989) Fingers of Instantiation (FINST) model consists of a fixed set (i.e. three, four, or five) of visual indexes or slots, called 'FINSTs', that can be assigned to objects to provide a connection between the outside world and visual representations in cognition (note Pylyshyn, 2001, added additional assumptions and modified some terminology but the basic claims remain) (see Figure 1.1, panel A). FINSTs are characterised as preconceptual[1] because they do not encode information about object identities; rather they stick to the object during motion supporting automatic tracking. There is evidence in support of this model from other visual paradigms (note this is a theory of vision, rather than a specific theory of MOT) including visual search and subitizing (e.g. Pylyshyn, 1994; Pylyshyn, Burkell, Fisher, Sears, Schmidt, & Trick, 1994), which also show a capacity limit of four or five objects, supporting the notion of a fixed architectural system.

Yantis (1992) proposed a perceptual grouping model which argues that, during tracking, targets are grouped into a higher order visual representation (i.e. three targets into a triangle, four targets into a quadrant) (see Figure 1.1., Panel B). Yantis (1992) showed that tracking was better when the higher order object remained intact during tracking compared with when it collapsed indicating that participants' ability to maintain perceptual grouping affects tracking performance. Both Yantis' (1992) grouping formation and Pylyshyn's (1989) indexing are proposed to be pre-attentive indicating some similarity between these two models. However, the maintenance of grouping during tracking is effortful and attentionally demanding whereas Pylyshn's FINSTs are automatically attached to targets during the tracking phases. Fehd and Seiffert (2008) monitored eye-movements and revealed that observers tend to fixate the (invisible) centroid rather than the individual objects during tracking, furthersupporting a centroid-tracking mechanism. They then showed that

[1] This was called 'preattentive' in earlier work but was changed to make it clear that focussed attention can play a role in tracking

centroid-looking behaviour is predictive of successful tracking (Fehd & Seiffert, 2010). Lukavsky and Děchtěrenko (2013; 2016) showed that there is stability in eye-movements across repetitions of trials which further suggests that a standard grouping mechanism might be used on every trial, regardless of the object movements. Nevertheless, properties of moving objects including object speed (Huff, Papenmeier, Jahn, & Hesse, 2010), tracking load (Zelinsky & Neider, 2008) and inter-object spacing (Zelinsky & Todor, 2010) have been shown to alter fixation behaviour. Specifically, an increase in speed, tracking load and reduced inter-object spacing leads to an increase in centroid looking. Overall, the pattern of results supports the idea of an automatic grouping during tracking.

Cavanagh and Alvarez's (2005) multifocal theory posits that multiple foci of attention track each object by supporting continuous attentional access to the objects being tracked (see Figure 1.1, Panel C). Evidence in support of multiple foci of attention comes from Alvarez and Cavanagh's (2005) research showing that participants were able to track twice as many objects when they were equally distributed across hemifields, demonstrating independence in the capacity to attentively track targets in the left and right visual hemifields. This rules out the possibility of a single focus of attention that cycles through each target to support tracking. Howe, Cohen, Pinto and Horowitz (2010) adapted the simultaneous-sequential paradigm (Eriksen & Spencer, 1969) within MOT. In the simultaneous condition all objects moved and paused simultaneously whereas in the sequential condition the objects were randomly divided into two groups that moved alternatively. There was no difference in tracking accuracy between objects in the simultaneous and sequential conditions. This shows that attention is spread in parallel, supporting the notion of multiple foci of attention. Importantly, however, there is evidence suggesting serial components to tracking (e.g. Howard, Masom, & Holcombe, 2011; d'Avossa, Shulman, Snyder, & Corbetta, 2006; Holcombe & Chen, 2013). In line with Pylyshyn (1989) and Yantis (1992), this model suggests that the limitation on tracking are due to architectural constraints such as the number of attentional foci.

1.5.2 Flexible Theories of MOT

Flexible resource theories suggest that there is a continuous pool of the attentional resource that can be drawn upon for tracking multiple objects. These theories emerged following findings that participants could track up to eight targets simultaneously (e.g. Alvarez & Franconeri, 2007), although capacity limits were below four or five when the objects moved at fast speeds (Alvarez & Franconeri, 2007; Holcombe & Chen, 2012). Research showing expertise effects, with certain populations (e.g. video gamers) being able to track more than four objects (Green & Bavelier, 2006) and individual differences in tracking ability (e.g. Oksama & Hyönä, 2004), also challenge fixed architectural accounts of tracking.

Alvarez and Franconeri (2007) proposed the FLEX model (FLEXibly allocated indexes) which suggests that objects are tracked by flexible indexes (FLEXes), with the total number of indexes limited by the finite resource (see Figure 1.1, Panel D). The limit on tracking is set by this shared resource that determines the resolution of each FLEX such that when fewer items are tracked, the tracking resolution is higher, consistent with findings relating to spatial precision of target representations (Howard & Holcombe, 2008; Howard, Masom, & Holcombe, 2011). Tracking errors arise when the attentional resource is insufficient to cover the demands (e.g. speed, proximity) of all targets, which is supported by Horotwiz and

Cohen (2010) who showed that the precision of trajectory tracking decreased with an increase in tracking load (i.e. more demands). It also explains well-documented phenomena across the MOT literature including flexible switching between tasks (Alvarez, Horowitz, Arsenio, DiMase, & Wolfe, 2005), or flexible switching between location and identity tracking (Cohen, Pinto, Howe, & Horowitz, 2011). Nevertheless, it has been criticised for not fulfilling the criteria of a good scientific theory (Meyerhoff, Papenmeier, & Huff, 2017) because it is under specified.

Franconeri, Jonathan, and Scimeca (2010) proposed the spatial interference theory of MOT which suggests that the constraints on tracking are determined by the spatial relationship between targets and distractors (i.e. objects that participants do not have to keep track of) (see Figure 1.1, Panel E). This alternative to the FLEX model suggests tracking errors are the result of distractors or other targets entering the inhibitory surround (i.e. a spatial region) of targets (Meyerhoff, Papenmeier & Huff, 2017). This is supported by Holcombe, Chen, and Howe (2014) who showed that attentional tracking can be impaired by the presence of a second object, particularly when that second object is another target, thus highlighting the role of spatial interference.

1.5.3 Hybrid models of Visual Working Memory

A parallel debate persists in the visual working memory (VWM)[2] literature in which a capacity limit of 3-5 items has often been reported (Cowan, 2001). Such findings have led to the proposal of fixed, slot-based theories of VWM which suggest that, irrespective of the

[2] Visual working memory and visual short-term memory are used interchangeably in the literature. Visual working memory is used throughout this manuscript for consistency and clarity.

complexity of objects, only a limited, fixed number of items can be stored (e.g. Awh, Barton, & Vogel, 2007; Luck & Vogel, 1997). Other authors (e.g. Alvarez & Cavanagh, 2004; Eng, Chen, & Jiang, 2005) propose that the number of objects that can be stored is more flexible and determined by the complexity of objects.

Utilising mixture models, Zhang and Luck (2008) obtained independent indexes of the capacity and resolution of VWM which contributed to the proposal of two hybrid models to explain the capacity limits of VWM. These models acknowledge that capacity limits could be the result of both a limited number of slots *and* a limited number of resources. The *slots + resources* model postulates that there are a fixed number of slots in memory but a variable resource exists that can be distributed unequally between these slots (Zhang & Luck, 2008). A *slots + averaging* model suggests that, when the number of items to be remembered is at or above capacity, each item has a single slot assigned to it. When fewer items are to be remembered, each item can be assigned more than one slot.

The ability to distinguish between fixed and flexible mechanisms underlies a variety of questions within cognitive psychology which are inherently related. Characterising the mechanisms that underlie tracking is therefore important to provide a greater understanding of other, related cognitive processes.

1.6 Adaptions of the MOT Paradigm

MOT research is commonly motivated by using real-world examples such as tracking cars, aircrafts or teammates. Therefore, developing the MOT task to more closely reflect these real-life situations can provide more naturalistic tasks that may facilitate investigation into the mechanisms that support tracking in everyday situations. To date, there have been several adaptions of the MOT paradigm to try to better capture real-world tracking.

Multiple Identity Tracking (MIT) requires participants to maintain information about both the spatial location and identity of an object because, in everyday life, objects typically have distinct identities that are relevant to the current task (e.g. Oksama & Hyönä, 2004). Horowitz, Klieger, Fencsik, Yang, Alvarez, and Wolfe (2007) used an MIT task using cartoon animals. There were two response modes. Participants either reported the locations of all target items or the identity of a particular object. The capacity for tracking multiple identities was lower than tracking multiple positions suggesting that there may be two separate systems: one carrying positional information and the other carrying identity information. Oksama and Hyönä (2016) compared tracking performance for identical objects and distinct objects with identities and also found the same pattern of results, further suggesting two separate and independent systems. Oksama and Hyönä (2008) present a serial model of multiple identity tracking (MOMIT). Identity-location bindings are refreshed serially and supported by a capacity-limited episodic buffer whilst a position tracking system monitors the positions of targets in parallel.

Wolfe and colleagues (2007; 2018) modified the MOT task to more closely capture components of real-world tracking. Wolfe, Place, and Horowitz (2007) explored the extent to which participants can *juggle* targets because, in the real-world, target items will change over time and it is rare that all target items are identified at one time point (i.e. the starting phase of a typical MOT task). Moreover, tracking in the real-world must often be maintained over minutes rather than seconds. Participants were able to juggle objects by selecting and deselecting the target at given time points with little cost to performance. Moreover, this ability could be maintained for up to 10 minutes at a time. Wu and Wolfe (2018) introduced a Multiple Object Awareness (MOA) measure within an MIT framework because they argued that approximate knowledge of an object's location is still knowledge that should be recognised. They reported that MOA capacity is at least double the capacity typically observed for identity tracking and highlighted the importance of utilising measures such as this within MOT research.

Thornton and colleagues (2014; 2015) introduced the interactive Multiple Object Tracking (iMOT) task to more closely capture tracking in the real-world whereby an individual must interact with their environment. For example, a driver must brake their car if one of the other cars they are tracking swerves in front of them. The iMOT task required participants to track multiple moving objects and prevent any collisions, by touching the screen, to gain an index of how many items an individual could *control* without collision. Participants could control (i.e. iMOT performance) more objects than they could track (i.e. standard MOT performance), but performance was positively correlated (Thornton, Bülthoff, Horowitz, Rynning, & Lee, 2014). Thornton and Horowitz (2015) then showed that planning and executing a display-relevant motor action did not impair on tracking performance.

Scott-Samuel, Holmes, Baddeley, & Cuthill (2015) used a single-object tracking task, inspired by the MOT task, within camouflage research to better understand how various parameters affect the confusion effect, whereby predators' success is reduced when prey group size or density increases due to a sensory bottleneck in which it is difficult to track one object among many. Tracking accuracy for a single object decreased as density and unpredictability of motion paths increased. In an adaption of this single object tracking task, Hogan and colleagues (2016, 2017) developed a task in which participants had to track the movement of a single target amongst other visually identical objects using a mouse. Average distance between the cursor and the target during the tracking period was taken as an index of tracking accuracy. Tracking accuracy increased when there was variation in the speed of the objects which was proposed to undermine the confusion effect (Hogan, Cuthill, & Scott-Samuel, 2017). Targets with stripes parallel to the direction of motion were harder to track than those with more conventional background matching patterns (Hogan, Scott-Samuel, & Cuthill, 2016; Hogan, Cuthill, & Scott-Samuel, 2016) demonstrating that dazzle camouflage, in which complex patterns effect the perception of an objects speed, direction and identity, enhances the confusion effect. Similar findings were shown in three dimensions, with the confusion effect revealed in a task where participants used a joystick to approach and 'catch' the target (Hogan, Hildenbrandt, Scott-Samuel, Cuthill, & Hemelrijk). Although such tasks do not require participants to perform MOT, many of the same cognitive processes are required.

1.7 New Adaptions to the MOT Task

The aim of this thesis was to modify the MOT task and response procedures to more closely reflect real world tracking and, therefore, gain insight into the underlying attentional resource.

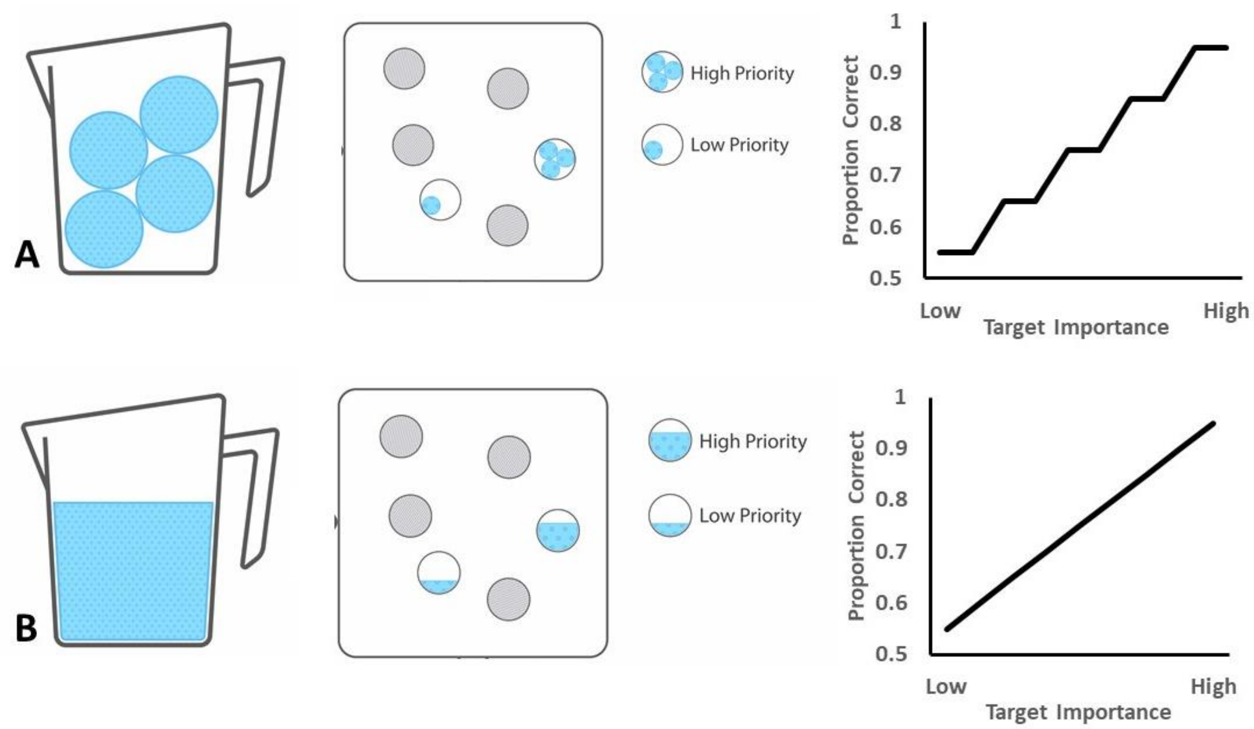
1.7.1 Unequal Attention Splitting

In standard MOT tasks, the relative importance of the targets being tracked is equal. This is atypical of everyday situations in which an individual may need to prioritise one target relative to another and so allocate attention unequally. For example, a driver would likely allocate more attention to the cyclist swerving in front of them than the pedestrian walking on the pavement, and a carer would likely prioritise monitoring a toddler over a teenager in a playground. Investigating participants ability to split attention unequally can provide insight into the nature of the resource underlying tracking. Both fixed and flexible theories are currently based on results from experiments using assumed equal attention splitting. Under either the fixed or flexible theories, unequal attention splitting, in which objects for tracking are allocated different amounts of the attentional resource, is theoretically possible. As an analogy to help distinguish the two accounts, water can be used to represent the attentional resource underlying tracking (see Figure 1.2). Under a fixed account, water takes the solid form of ice cubes and so the fixed number of ice cubes or slots can be unequally distributed across objects in only a limited number of ways (i.e. attention slots could be split between two targets according to a limited number of ratios: 4:0; 3:1; 2:2 or 5:0; 4:1; 3:2). In contrast, under a flexible account water takes the liquid form and so can be flexibly allocated unequally in any way (e.g. 37%:63%). Exploring if and how attention can be split unequally can distinguish these accounts. Under a fixed account, a stepped increase in performance as target priority increases is predicted whereas (Figure

1.2, Row A), under a flexible account, a graded increase in performance would be predicted (Figure 1.2, Row B).

Figure 1.2. Schematic diagram to demonstrate the analogy of water as the attentional resource taking either a A) Fixed or B) Flexible form.

It is important to recognise that the structure of the attentional resource could fall anywhere between these fixed and flexible accounts and so a key question to address is *how* flexible the resource is. Although currently not specifically developed within a MOT framework, hybrid models of attention have been proposed in the VWM literature (Zhang & Luck, 2008). A *slots + resources* model suggests that there are a fixed number of slots but



the resource can be unequally allocated between these slots. As an analogy, Zhang and Luck (2008) explain that there could be two cups (the slots) and one bottle of juice (the resource). One cup could receive most of the juice and another cup could receive only a few drops demonstrating an unequal allocation of the resource between two fixed slots. A *slots + averaging* model postulates a fixed number of slots, but more than one slot can be applied to a given target if below capacity. As an analogy, Zhang and Luck (2008) suggest that there might be four juice boxes available and these could be differentially allocated between two targets (i.e. 1 and 3 boxes to Target 1 and 2, respectively).

1.7.2 Manipulating Situational Factors

MOT is commonly undertaken in pressurised, anxiety-provoking environments such as the military, air traffic control and sport. Research is therefore warranted to understand the effect of state anxiety on performance within a MOT framework. Moreover, understanding the interplay between attention and anxiety provides insight into how the attentional resource operates in different conditions. There are many theories that explain the relationship between anxiety and performance (e.g. Beilock & Carr, 2001; Eysenck & Calvo, 1992) and, more recently, those that explain the effect of anxiety on attention, specifically (e.g. Eysenck, Derakshan, Santos, & Calvo, 2007; Easterbrook, 1959). The theory of attentional narrowing suggests that, in response to anxiety, the attentional window narrows (Easterbrook, 1959), with research showing that performance on a central task increases whilst performance on a peripheral task decreases. An unequal splitting MOT framework facilitates a direct test of this theory by exploring if state anxiety leads to a different distribution of the attentional resource under anxious compared with control conditions. Such investigation can also provide insight into the wider debate regarding the flexibility of the resource that underlies tracking performance.

1.8 Summary of Empirical Chapters

1.8.1 Chapter 2. Goal-directed unequal attention allocation during multiple object tracking

Adapted from: Crowe, E. M., Howard, C. J., Attwood, A. S., Kent, C. (2019). Goal-directed unequal attention allocation during multiple object tracking. *Attention, Perception and Psychophysics.* doi:10.3758/s13414-019-01674-y.

When tracking multiple objects in a dynamic environment one may need to prioritise one object over another and so allocate attention unequally. Chapter 2 introduces a novel MOT task that was developed to capture this element of real-world tracking and gain insight into the structure of the attentional resource. Target priority was manipulated to explore its effect on tracking performance in trajectory- and position-tracking tasks. Four studies showed that attention can be divided unequally between multiple moving targets. Specifically, more and less attention can be allocated to higher and lower priority targets, respectively, as indexed by the magnitude of error (Experiments 1 – 3). Modelled proportions of guessing responses and spread of errors were also affected by target priority, with a lower proportion of guessing and higher precision for high priority targets (Experiments 1 – 3). These results indicate some flexibility to the attentional resource which must be incorporated into models of MOT.

1.8.2 Chapter 3. Reward-based unequal attention allocation in position tracking

Adapted from a paper submitted to *Attention, Perception and Psychophysics.*

In Chapter 3, the unequal attention splitting MOT task was utilised to examine reward-based unequal attention allocation. Experiment 4 showed that participants could split attention unequally in a reward-based manner, supporting the results of Chapter 2. Experiments 5 and 6 introduce a double-probe procedure in which participants were required to report on the final locations of two targets presented simultaneously. A Tracking Accuracy Comparison (TAC) score was then obtained by calculating the difference in tracking accuracy between the two targets. This provided insight into the relationship between tracking accuracy for two targets. Both experiments revealed a main effect of reward, further indicating flexibility to the attentional resource, but there was no effect of splitting condition (i.e. unequal versus equal splitting) on TAC scores and no correlation in tracking accuracy for the two targets. There was, however, evidence for memory decay and interference in the dual-report tracking task, with poorer accuracy for the second target, highlighting the role of memory in a MOT paradigm.

1.8.3 Chapter 4. No evidence for attentional narrowing within a MOT framework

MOT is commonly undertaken in anxiety-provoking environments and, therefore, research exploring the effect of anxiety on MOT performance is warranted. In Chapter 4, the effect of state anxiety on MOT performance was investigated. More specifically, the unequal attention-splitting MOT task was used to test the theory of attentional narrowing. Attentional narrowing theories predict that, under anxiety, performance on a central task is better at the cost of performance on a peripheral task (Easterbrook, 1959). In line with this, we predicted that participants would direct more attention to the high priority target in the anxious compared with non-anxious condition. Experiment 7 manipulated anxiety using a cognitive anxiety induction technique, but the manipulation check showed that it was not successful at inducing anxiety. Therefore, Experiment 8 used a physiological anxiety induction technique, the 7.5% CO_2 challenge model of anxiety induction, which was successful at inducing anxiety. There was, however, no evidence for attentional narrowing. There was also no evidence for main effect of anxiety on performance when all participants were grouped together. Exploratory analysis showed that some participants demonstrated an increase in performance during the inhalation of CO_2 whereas others performance decreased, which resulted in there being no overall main effect. The implications of this finding for anxiety research is discussed.

1.9 Apparatus and Task

Unless stated otherwise, the following apparatus was used. Experiments were programmed in MATLAB (The MathWorks Inc, 2014) and the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). Participants' responses were recorded using a standard mouse and USB keyboard. All tasks were completed in a dimly lit room and viewing distance was approximately 40 cm. Stimulus displays were presented on a 17-inch CRT monitor with a resolution of 1,024 x 768 pixels and a refresh rate of 85Hz.

On each trial, participants fixated a central black fixation cross with eight black discs with a radius of 1.14° of visual angle. The two targets and six distractors were presented simultaneously on a mid-grey screen at the start of each trial for 2,000 ms. At the start of each trial, each target had a number presented on it denoting either the likelihood of that target being queried at the end of a trial or the number of points that a participant would be rewarded for correctly tracking that target. The discs then moved randomly around the screen at an average speed of 15.8° (range 12.75° – 21.95°) per second for between 5,000 - 8,000 ms (randomised for each trial) and underwent perfectly elastic collisions whenever they collided with the edge of the display or another disc. At the end of a trial, participants performed either a trajectory- or position-tracking response.

Trajectory Tracking. At the end of the trial, all discs disappeared except one of the targets, which remained on the screen. Participants clicked inside the target to activate it which caused a line, 1.14° long, to extend from the targets' centre. The direction of the line was determined by the position of the participants mouse click. Participants then moved the line (using the mouse) to report the target's trajectory and clicked to confirm their answer. Feedback, consisting of a arrow indicating the correct direction of heading, was given on each trial for 2,000 ms, after which the next trial was presented (see Figure 1.3).

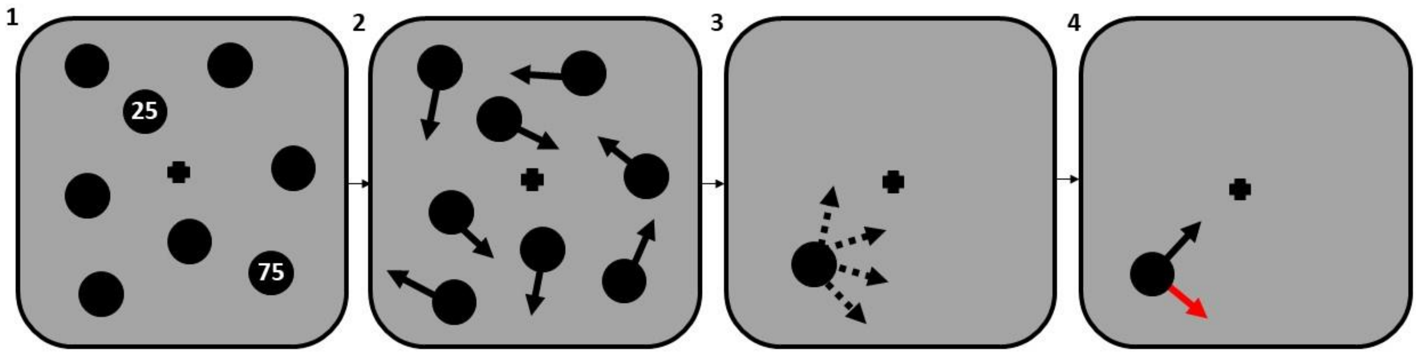


Figure 1.3. Trajectory-tracking task trial timeline. 1) Eight discs are presented on screen; 2) All discs moved around the screen (note the arrows were not presented on screen); 3) All discs except one disappeared. Participants estimated what direction the disc was heading in

at the end of the trial using a rotatable pointer; 4) Participants were given feedback. A second arrow was presented which indicates the correct target trajectory. If a participant's trajectory estimate was within 15 degrees of the correct trajectory, the arrow turned green. Otherwise, it turned red.

Position Tracking. At the end of a trial, all discs disappeared. Participants were verbally instructed, via headphones, to *localise* one of the targets. Localisation required participants to move the mouse cursor and left-click the position that they thought the cued target occupied at offset. After a response had been made, the correct position was indicated by redisplaying the target item in its correct final position. The disc representing the participant's estimated final position of the target was also shown coloured green (correct) or red (incorrect), depending on whether selected coordinates fell within the circumference of the target or not. Feedback was given for 2,000 ms, after which the next trial started (see Figure 1.4).

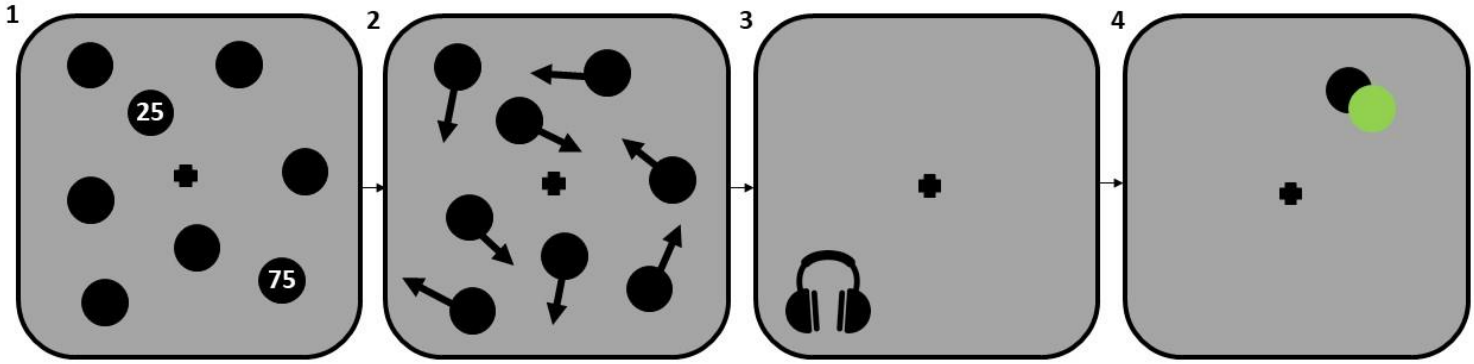


Figure 1.4. Position-tracking task trial timeline. 1) Participants are presented with a starting screen consisting of a central fixation cross and eight black discs; 2) The discs then move around the screen (note the arrows were not presented on screen); 3) All of the discs then disappear, and participants are cued, through headphones, which target to localise; 4)

Participants are given feedback on their response. Their guess turned green if they were correct or red if they were not.

1.10 Ethics and Pre-registration

Ethical approval was granted by the University of Bristol, Faculty of Life Sciences Research Ethics Committee for all studies. All participants reported normal or corrected-to-normal vision and hearing. Written informed consent was obtained from all participants. The study aims, hypothesis and design for all studies (excluding Chapter 2, Experiment 1) were pre-registered prior to data collection on the Open Science Framework (https://osf.io/myprojects/)[3].

1.11 Pre-registration

Following the reproducibility crisis (e.g. Aarts et al., 2015; Munafò et al., 2017; Nosek, Ebersole, DeHaven, & Mellor, 2018), there has been an increasing focus on pre-registration to help improve the reliability and credibility of research (Munafo et al., 2017). Therefore, most experiments in this thesis were pre-registered on the OSF. Specifically, the study background, aims, hypothesis, design, sample size calculation and statistical analysis were all planned prior to data collection (i.e. the strongest form of pre-registration). Pre-registration clearly distinguishes between the two stages of science: 1) Exploratory (i.e. hypothesis generation); 2) Confirmation (i.e. hypothesis testing). One aim of pre-registration is to overcome publication bias and analytical flexibility (Munafo et al., 2017). Studies that reveal positive results are more likely to be published (Franco, Malhotra, & Simonovits,

[3] All deviations from the initial pre-registration on the Open Science Framework are reported in Appendix 1.

2014), and researchers have been known to modify their statistical plan to report and highlight those that show statistical significance, thereby increasing the chances of publication. This ultimately leads to an increase in the chance that spurious results, contingent on potential p-hacking are published (Simmons, Nelson, & Simonsohn, 2011). Whilst pre-registration is beneficial in principle, in practice I have found it to be a difficult process during the course of my PhD. Whilst I advocate open science, I think that current pre-registration practices need refinement.

During my PhD I have gained experience with the publication process and, ultimately, have edited my papers to favour the reviewer's preferences. Such modifications include shortening the manuscript, modifying exclusion criteria and running different analysis which has led to several deviations from my initially pre-registered work. In one example, I edited the main analysis conducted to investigate the effects of interest which largely strengthened the paper. However, this resulted in extensive discussion regarding the extent to which I could claim pre-registration of my study because the primary statistical analysis was not what was initially stated. Whilst I understand concerns regarding phishing, I do not agree that this additional analysis constituted phishing. It was suggested externally by someone who had no access to the data, rather they had knowledge of an analysis that would fit the data we had collected. In other disciplines, such as epidemiology, large amounts of data are collected because they *might* be of interest. It is only later down the line that research questions are formulated, and hypothesis tested using a trial and error process of the most up-to-date method which results in re-analysis of the same data set numerous times. I therefore do not think it is fair to argue that *all* the research presented in this thesis is exploratory, rather than confirmatory.

My proposal to overcome such issues is to peer review pre-registrations. Developing research questions, hypothesis, study designs and statistical plans is difficult and would largely benefit from the input of numerous experts in one's field of research whereas collecting data and then following a clear analysis plan is *easier*. I therefore think the recently emerging "registered -reports", in which a preregistration proposal is approved and "in-principle acceptance" where final publication does not depend on the results in obtained, are a good idea. It also allows one to improve the preregistration proposal based on the reviewers' comments, namely before data collection and before it is "too late". Nevertheless, a large problem with this process is time and career pressures. Throughout my PhD there has been an ever-increasing requirement to publish but still an extremely long review process. Rather than running pilot studies, and developing ideas before pre-registration, we delve straight into the answering of a specific research question because of an increased pressure to publish. Therefore, whilst one manuscript is peer-reviewed, the next series of experiments, which may have fundamental issues or could be drastically improved by reviewers' comments, has already been pre-registered including all the limitations of the previous work. This is ultimately a vicious cycle that would require modification to current practices (i.e. requirement for registered reports) and a shift in focus for career development (i.e. high quality rather than high volume research articles). My overall impression is that collaboration and peer review are more effective and beneficial at the conception of a study, rather than much later in the publication process where it is arguably *too late.*

1.12 Data Analysis

Unless stated otherwise, Linear Mixed Effects models (LMEs) (Baayen, Davidson, & Bates, 2008; Barr, Levy, Scheepers, & Tily, 2013) were used to analyse the data using the lme4 package (Bates, Mäechler, Bolker, & Walker 2014) for the R computing environment (R Development Core Team, 2014). All full models included a random effect of participants. Additional random effects and interactions were only added when the more complex mode fit the data significantly better according to a likelihood ratio test. For each experiment, the random and fixed effects included in each full model are reported. The *t*-statistics from the full model (even if the model contained non-significant main effects and interactions) alongside p-values from the model comparison procedure are reported. Post-hoc comparisons were conducted by comparing the slopes between two adjacent data points.

Chapter 2 Goal-directed unequal attention allocation during multiple object tracking

2.1 Chapter Summary

In standard multiple object tracking (MOT) tasks the relative importance of the targets being tracked is equal. This is atypical of everyday situations in which an individual may need to prioritise one target relative to another and so allocate attention unequally. Three experiments were designed to examine whether participants could unequally split attention using a modified MOT task in which target priority was manipulated. Specifically, the effect of priority on participants' magnitude of error was examined using a distribution mixture analysis to investigate how priority affected both participants' probability of losing an item and tracking precision. Experiment 1 (trajectory tracking) revealed a higher magnitude of error and higher proportion of guessing for the low compared with high priority targets. Experiments 2 (trajectory tracking) and 3 (position tracking) examined how fine-grained (i.e. the precision of splitting) unequal attention splitting is by manipulating target priority at finer increments. In line with Experiment 1, results from Experiments 2 and 3 indicated that participants could split attention unequally. There was some evidence that participants could allocate attention unequally at fine increments, but this was less conclusive. Taken together, these experiments demonstrate participants' ability to distribute attention unequally across multiple moving objects, albeit with some limitation.

2.2 Introduction

Everyday activities require us to split our attention unequally between moving objects. However, current theories describing the attentional resource underlying tracking are based on results from experiments using assumed equal attention splitting. Under both fixed and flexible theories, unequal attention splitting is theoretically possible, but these theories predict different patterns of results (see Figure 1.2). Therefore, researching investigating participants' ability to split their attention unequally can help distinguish between fixed and flexible theories of tracking.

Previous studies have demonstrated stimulus-driven unequal allocation. Liu et al., (2005) modified the typical MOT task so that half the objects moved at 1 degree/s and the other half at 6 degree/s. Since objects moving slower are typically tracked more accurately than those moving faster (Pylysyhn & Storm, 1988; Yantis, 1992), the authors expected poorer tracking accuracy for the faster moving targets. There was no difference in tracking performance between fast- and slow-moving targets, indicative of unequal attention allocation. More specifically, more of the resource could have been allocated to the faster (more demanding) target, which resulted in similar tracking accuracy across both speed conditions. Chen, Howe, and Holcombe (2013) compared the speed limits at which participants could track a critical target when the second target was moving at either the same or a slower speed. The speed limit for the critical target was higher if the second target was moving slowly rather than fast. This suggests that participants allocated attention unequally, with more attention available to allocate to the fast-moving target when the secondary target was moving slower. Together, these results provide evidence consistent with participants' ability to unequally allocate attention in a stimulus-driven manner.

Some authors have also examined participants' ability to shift attention on-line (i.e. during a trial). Iordanescu, Grabowecky, and Suzuki (2009) argued that targets in crowded situations (i.e. those in danger of being mistaken for distractors) were localized more precisely than uncrowded targets, suggesting that more attention was allocated to these ‘high risk’ targets. This supports the notion of unequal attention allocation and, additionally, suggests that the attention allocated to a given target can be changed during tracking. Nevertheless, this result should be interpreted with some caution because proximity (to the nearest distracter) was not manipulated directly (i.e. object trajectories were randomly determined) and, therefore, other display characteristics could have been affected as well as proximity (Chen, Howe, & Holcombe, 2013; see also contradictory findings by Howard, Masom, & Holcombe, 2011). Howe et al. (2010) adapted the ‘simultaneous-sequential paradigm’ (Eriksen & Spencer, 1969) to examine whether attention could be reallocated between targets during tracking. In the simultaneous condition, all objects moved and paused simultaneously whereas in the sequential condition objects were divided into two groups and moved alternatively. There was no difference in tracking performance between objects in the simultaneous and sequential conditions which suggests that participants could not reallocate attention unequally between targets during tracking. Meyerhoff, Schwan, and Huff (2018) conducted a series of experiments to explore whether inter-object spacing guides visual attention. A bias towards temporarily close objects (both in term of spatial attention allocation and eye movements), which persisted even when the bias was harmful for the task, was observed indicating both unequal attention allocation and updating of attention allocation during a trial (see also, Zelinsky, & Todor, 2010). In other work Meyerhoff, Papenmeir, Jahn, and Huff (2016) revealed that such unequal allocation of the attentional resource in a stimulus-driven manner is advantageous to avoid confusion between targets and close distractors indicating that attention can be flexibly allocated during tracking.

Goal-directed unequal attention allocation in MOT has also been documented. Cohen, Pinto, Howe, and Horowitz (2011) modified the instructions given to participants in a MIT task. In one condition, participants were instructed to prioritise the locations over the identities of target and, in another, were instructed to place equal emphasis on both location and identity information. Position tracking performance was higher when prioritisation instructions were given demonstrating unequal attention allocation between the location and identity information associated with the same target. However, to our knowledge, no research has addressed whether participants can split attention unequally between distinct targets (i.e. not to different features of the same object but to different objects entirely) in a goal-directed manner. Examining the way in which participants can split attention unequally in a strategic manner has the potential to inform the debate regarding the structure of the attentional resource underlying tracking because the amount of attention allocated to a given object can be directly manipulated. This allows examination of the resource-versus-performance function, the shape of which would be different for fixed and flexible theories. As well as being theoretically important, unequal allocation of attention is highly relevant to the real-world in situations where one wishes to prioritise, and so allocate more attention to one target over another target, which nonetheless needs tracking.

Yantis (1992) showed goal-directed attention allocation within a MOT framework. Participants who were instructed to group all targets together displayed higher tracking accuracy than those who were given neutral tracking instructions. This shows that participants modified their tracking strategy in a goal-directed manner. Brockhoff and Huff

(2016) combined a typical MOT task with a non-interfering top-down identification task. Participants were instructed to identify the behaviour of dynamic cartoon eyes. The cartoon eyes were the objects in the MOT task and the moving pupils cued either a single target or single distractor by all rotating to look towards that specific object. Participants could ignore or prioritise objects based on cueing, thus indicating goal-driven attention allocation during the MOT task. Taken together, these results demonstrate top-down mechanisms driving attentional allocation but do not provide any insight into the potential for top-down *unequal* attentional allocation between two simultaneously tracked objects within a trial.

Goal-directed unequal attention allocation has been demonstrated in other attention-based tasks in which participants are instructed to allocate different proportions of their attention accordingly. Miller and Bonnell (1994) instructed participants to pay a certain amount of attention to a line-length discrimination task on the left side of the screen and the remaining attention to the right side and revealed that sensitivity increased with the proportion of attention devoted to that side. Fitousi (2016) instructed participants to allocate differential amounts of their attention to the top and bottom halves of a face. Such instructions were effective in modifying the amount of attention allocated to either half of the face, with participants' performance improving as a function of attention allocation (Fitousi, 2016). Atkinson, Berry, Waterman, Baddeley, Hitch, and Allen (2018) used probe frequencies (i.e. how frequently a more valuable item was tested) to examine whether memory for an item was enhanced if participants were told it would be tested more frequently. Memory was enhanced for the relatively more valuable item indicating that attention can be directed according to probe frequencies. Using an effortful visual search task, Jiang, Sha, and Remington (2015) cued spatial attention to one visual quadrant using either goal-driven instructions (i.e. instructing participants to prioritize it), location probability learning (i.e. placing the target there frequently) or reward (i.e. associating it with higher monetary gain). Results showed that successful goal-driven attention exerted the strongest influence on search response time which indicates that participants strategically allocated more attention, indexed by shorter reaction times, to the cued quadrant in a top-down manner. However, Chen, Howe, and Holcombe (2013) suggest that it would be difficult to induce participants to allocate a specific proportion of attention to two targets during a MOT task due to the extended duration of tracking across a MOT trial. We empirically test this claim here.

A pilot experiment from our lab showed that participants could allocate more attention to an 'über-target' than to three standard targets using a two-alternative (i.e. target or distractor) forced choice task. The results showed that participants could allocate attention unequally dependent on top-down control, warranting further investigation into this ability. However, there were limitations with this experiment. The two-alternative forced choice response used to assess tracking performance yields only binary data (correct or incorrect). Although this is typical of many MOT studies, using a continuous measure of tracking accuracy, such as the magnitude of error for trajectory or position tracking, offers a more precise measure of attention allocation. In addition, it is possible to interpret the distribution of error magnitudes in order to test whether the difference in overall accuracy is due to increased guessing (as for example when participants lose track completely of an target), or a difference in the precision (due to the amount of allocated attention) of the tracked target. Another limitation was that participants were instructed to allocate 'most' of their attention to the über-target but no values detailing what 'more' constituted were provided. It is possible, therefore, that one participant may interpret ‘more’ as 90% and another participant as 60% of their attentional resource so leading to variation in the prioritisation strategies adopted by participants. A more objective method for detailing the priority of targets might facilitate control of prioritisation strategies across participants. Subsequent research is required to overcome these limitations.

Three experiments examined whether participants could split attention unequally to multiple moving objects in a goal-directed manner. An unequal attention splitting MOT task was developed in which the priority of targets was manipulated to examine the effect of target priority on tracking performance. Such modification resulted in the task encompassing components of both MOT and MIT. MIT requires participants to maintain location-identity bindings during tracking (Mayerhoff, Papenmeier, & Huff, 2017). This modified MOT task requires participants to assign a priority (i.e. an identity) to each target during a trial and therefore fits with an MIT task. However, the index of tracking performance fits more closely with the MOT literature because the targets’ position or trajectory is queried rather than an identity-related response.

Experiment 1 examined whether participants could split attention unequally between high and low priority targets. Experiment 2 and 3 explored how fine-grained participants’ ability to allocate attention unequally was by manipulating the target priorities at finer increments. Tracking performance was measured as the absolute error between the actual and estimated trajectory (Experiments 1 and 2) or location (Experiment 3). In addition, a mixture distribution analysis (based on Zhang & Luck, 2008) was used to estimate the precision of tracking and the guessing rate. We hypothesised that the magnitude of tracking error and proportion of guessing would be lower, and the precision of tracking would be higher for the higher priority targets in all three experiments indicative of strategic unequal attention allocation.

2.3 Experiment 1

Experiment 1 aimed to overcome the limitations that were present in the pilot experiment.The error between the actual and estimated trajectory was used as a continuous measure of tracking accuracy and Zhang and Luck's (2008) distributional analysis was used to estimate the proportion of guess trials, and the precision of the tracked targets. Participants were explicitly told the percentage of attentional resource that they should attempt to allocate to a given target at the start of each trial.

2.3.1 Method

Participants. Twenty-seven undergraduate students from the University of Bristol participated in return for course credit. G*Power version 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) was used to calculate sample size for all experiments. Based on existing data from our lab suggesting an effect size of *dz* = 0.73 for comparison between targets with a 25% and 75% likelihood of being probed, this sample size gave us a 95% chance of observing a similar effect size, with alpha set at .05 for two-tailed tests.

Design. Target priority was manipulated in a within-subject design with three levels: low (25%), equal (50%), and high (75%) which reflected the veridical probability of a target being queried over the course of the whole experiment. The primary dependent variable was magnitude of angular error, indexed by the degree of error from the queried target's actual trajectory (i.e. the direction it was heading in) to the participant's reported trajectory at the end of the trial. For example, if at the final moment of the moving tracking display, the queried target was last moving upwards and rightwards at an angle of 10 degrees clockwise from vertical, and the participants reported that it was moving directly upwards, then this would constitute a magnitude of angular error of 10 degrees. The proportion of guess trials and precision of representations calculated from the mixture modelling analysis were also dependent variables.

Procedure. The trajectory tracking task was used. At the start of the trial, each target had one of three numbers (25, 50, 75) presented on them denoting the likelihood of this target being queried at the end of a trial and so indicating the relative importance of each target (i.e. the 75 and 25 targets were of high and low priority respectively). On any given trial, the combined values totalled 100. Participants were given clear instructions and the opportunity to ask questions on how to allocate their attention before starting the practice trials. Participants completed 10 practice trials followed by 250 experimental trials, the order of which was randomised, in 10 blocks. The experiment lasted approximately 1 hour.

2.3.2 Results and Discussion

One participant was excluded due to their very high magnitude of error (and the model-based analysis suggested they had a very high rate of guessing). LME analysis was used. Target priority was entered into the model as a fixed effect. As random effects, there was a random intercept for subjects and a by-subject random slope for the effect of target priority.

There was a main effect of priority, $\chi2$ (2) = 16.60, $p < .001$, whereby the magnitude of angular error decreased as target priority increased, $b = -0.277$, $SE = 0.06$, $t = 4.42$. Post-hoc tests showed that there was a higher magnitude angular error in the low priority than equal priority condition ($b = -0.48$, $t = 3.53$, $p = .006$), but no difference between the equal and high priority conditions ($b = -0.08$, $t = 1.65$, $p = .236$) (see Figure 2.1, left panel).

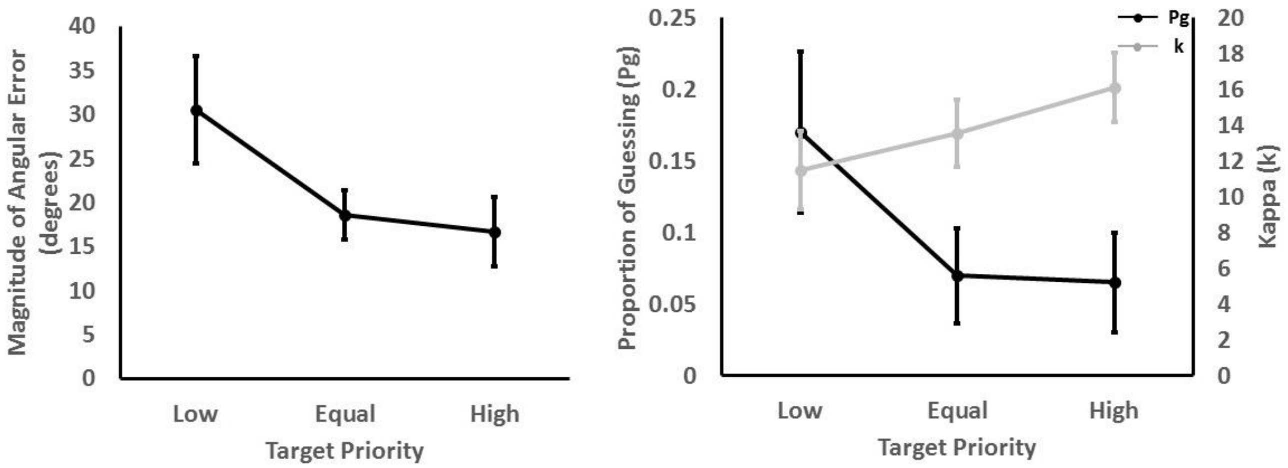


Figure 2.1. Mean magnitude of error, proportion of guessing and precision of tracking for each target priority in Experiment 1. Error bars represent 95% within-subject confidence intervals using Morey (2008).

It is possible to interpret the distribution of error magnitudes in order to examine the data further. This analysis distinguishes contributions from two sources to differences in overall accuracy. The first source is the guessing rate, where guesses may be due to participants losing track or otherwise completely withdrawing attention from a target. The second is the precision of representations (due to the amount of allocated attention) of targets[4]. Analysing data from a series of MOT experiments in which participants judged the heading of a target object, Horowitz and Cohen (2010, following Zhang & Luck, 2008) used a mixture of a uniform distribution (representing the situation where a target is lost and participants must guess) and von Mises (the circular equivalent of the normal distribution), representing the situation where participants have successfully tracked a target, but with varying precision, as reflected in the spread of the distribution). Under a pure slot-based model the precision should not change as set size increases to any level (since a fixed number of slots are allocated, and targets that are not tracked are guessed, which is captured under the uniform guessing distribution). Flexible accounts predict that precision should decrease as the number of items increases for any set size increase. Horowitz and Cohen also tested two hybrid models (again following Zhang & Luck, 2008): the *slots + resources* model (a fixed number of slots, but a resource that can be unequally allocated among those slots) and the *slots + averaging* model (a fixed number of slots, but slots can be applied to more than one target if below capacity). Both hybrid models make the same prediction however: if the number of targets to track is below capacity the precision will decrease as the number of targets increase (either because resources are spread more thinly, or because slots cannot be shared) and asymptote if capacity is reached (as additional targets are not tracked and are guessed, which is captured under the uniform guessing distribution).

In line with the method used by Horowitz and Cohen (2010), we fit a mixture of a uniform circular distribution and von Mises distribution to each participants' data for each

[4] We thank H. Meyerhoff for suggesting this analysis.

level of priority. We used the fitdistr function from the 'MASS' package (Venables & Ripley, 2002) with von Mises and uniform distributions functions from the 'circular' package (Agostinelli & Lund, 2017). The uniform circular distribution, representing the situation where a participant makes a guess response, generates a random value between -180 to 180. The von Mises distribution, representing the situation where a participant has tracked a target, but to a varying degree of precision, is controlled by two parameters: μ (the mean) and κ (the concentration parameter, which determines the spread of the distribution). The mixture of guessing and tracked errors was controlled by P_G, the proportion of guessing. The error distribution, ε, is therefore:

$$\varepsilon = P_G f_{uc}(-180,180) + (1 - P_G) f_{VM}(\mu, \kappa), \quad (1)$$

In which f_{uc} is the uniform circular distribution function and f_{vm} is the von Mises distribution function. In our analysis (following Horowtiz & Cohen, 2010) we fixed μ = 0 (i.e. average error was zero). We used R (R Core Team, 2015) to estimate κ and P_G values via maximum likelihood estimation function fitdistr from the MASS package (Venables & Ripley, 2002) with von Mises and uniform distributions functions from the 'circular' package (Agostinelli & Lund, 2017). The mixture model fits (for data combined across participants), for each level of target priority, are shown in Figure 2.2). A higher concentration value, κ, demonstrates higher precision.

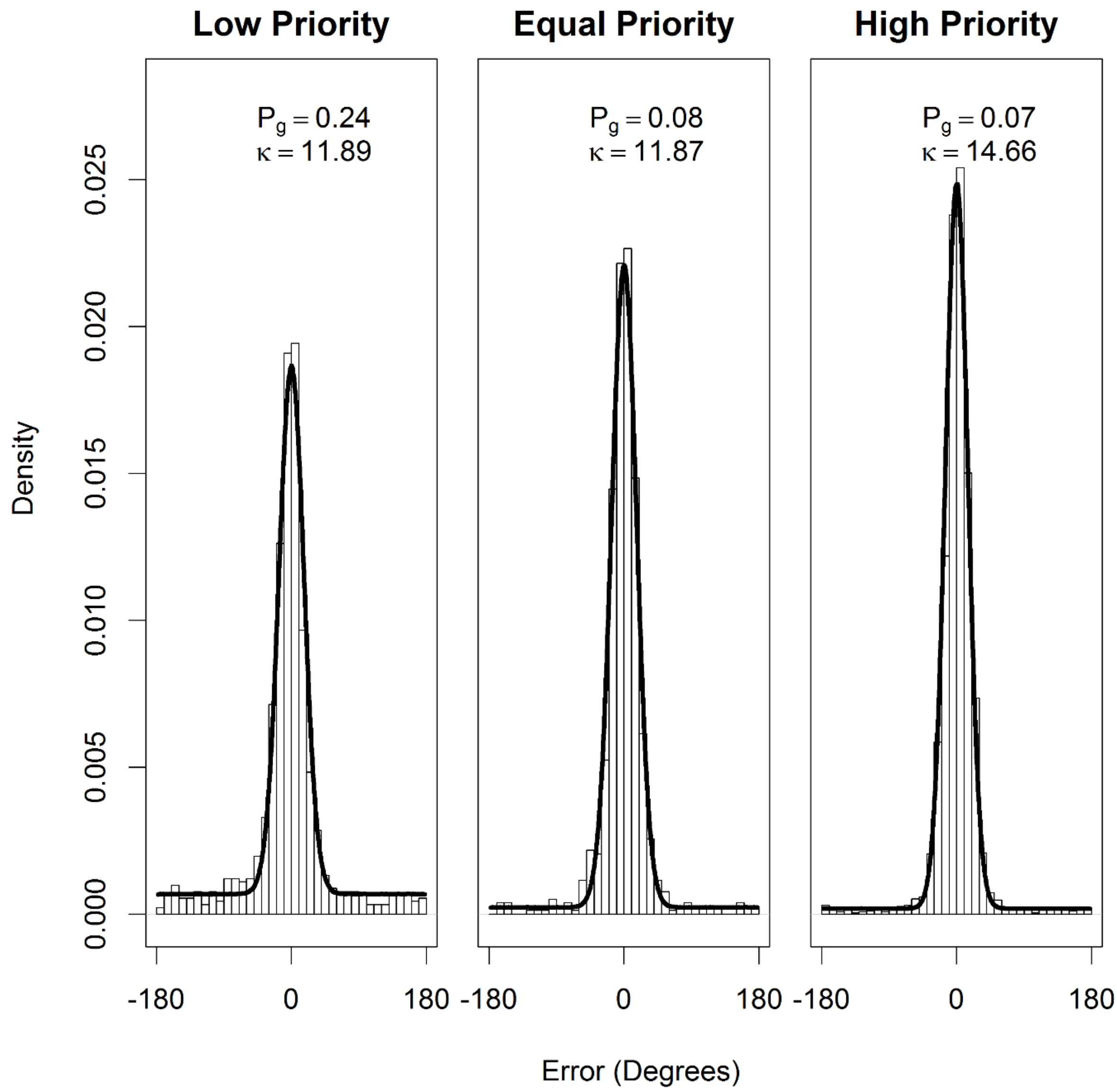


Figure 2.2. Mixture model fits for the combined data across participants for Experiment 1 for each level of target priority. The density plot displays the actual data and the black line shows the model fit. The proportion of guessing (P_G) and precision of tracking (κ_{VM}) parameters are also detailed.

The κ and P_G values, estimated for each participant and each level of priority, were then entered into a LME analysis, in an identical manner to the treatment of the magnitude of angular error scores. There was an effect of target priority on the proportion of guessing, $\chi2$ (2) = 11.10, p = .004. Participants demonstrated less guessing for high priority targets, b = -0.002, SE = 0.001, t = 3.52. There was evidence for a higher proportion of guessing in the low priority compared to the equal priority condition, (*b* = -0.004, *t* = 0.32, *p* = .021). However, there was no difference in the proportion of guessing in the high compared with equal condition, (*b* = -0.004, *t* = 1.65, *p* = .950) (see Figure 2.1, right panel).

Finally, there was an effect of target priority on the precision of representations (κ), $\chi2$ (2) = 10.52, *p* = .005, with the precision increasing as target priority increased, *b* = -0.09, *SE* = 0.03, *t* = 3.42 (see Figure 2.1, right panel). Post-hoc tests showed that there was no difference in precision between any of the adjacent levels of target priority (both *t* < 2.12 , *p* > .127).

This experiment showed that participants guessed the trajectory of the low priority target more frequently than both the equal and high priority target. Howard, Rollings, and Hardie (2017) showed that participants' attention to a target's position and its motion characteristics are distinct. Therefore, it cannot be assumed that all guess trials were associated with participants having no attention on that target. However, it could be argued that the higher proportion of guessing for low priority targets indicates participants could not split attention unequally and, therefore sometimes either lost the target completely (i.e. dropped the target) or confused it with a distractor (i.e. swapped the target with a distractor). However, this is likely an infrequent occurrence given the relatively low proportion of guessing (the majority of trials not modelled as involving a guess response) and a relatively good level of tracking accuracy (indexed by the magnitude of angular error) for the low priority target. This indicates that some attention was allocated to the low priority target but, in some cases, this was not sufficient to support updating of a targets' trajectory which resulted in an increase in guessing.

The effect of target priority on magnitude of error and precision shows that differential amounts of attention were allocated to the high and low priority targets, respectively, indicative of unequal attention allocation. This suggests some flexibility to the attentional resource underlying tracking. Specifically, more attention is allocated to the high priority target which leads to a lower magnitude of error and higher precision. This finding does not fit with slot-based accounts of attention allocation which would predict that the magnitude of angular error and precision of representations would remain constant because each target is allocated one slot. Flexible and hybrid models can, however, account for these findings because under their assumptions attention is unequally distributed between the two targets resulting in differences in the three indexes of tracking accuracy.

This experiment does not provide insight into how fine-grained this ability is. The extent to which attention splitting is fine-grained refers to the precision with which a division of attention is possible, in an analogous fashion to the way that liquid water makes splitting infinitely more fine-grained than crushed ice or ice cubes. Experiment 2 therefore examined whether participants can split their attention unequally across two targets with smaller disparities in their priority (e.g. 40% vs 60%) than used in Experiment 1 (i.e. 25% vs 75%). Exploring the extent to which attention is fine-grained has the potential to distinguish between different models of MOT. In fixed models attention can only be split unequally in a finite number of ways (i.e. 4-0; 3-1; 3-2). In contrast, under flexible accounts, there is an unlimited number of ways that attention can be split.

2.4 *Experiment 2*

Experiment 2 further investigated to what extent participants can finely split their attention unequally across multiple moving objects. We manipulated the target priorities at finer increments (70, 60, 50, 40, and 30) than Experiment 1 to enable investigation of the precision with which participants could allocate a pre-specified amount of the attentional resource to a given target. We conducted two identical studies, but one was completed in a single participant testing environment (i.e. each participant completed the study alone) and another was completed in a group testing environment (i.e. participants completed the study in a group of approximately 20 participants). For brevity and power, we present the combined data from these studies[5].

2.4.1 Method

Participants. Seventy-nine undergraduate students from the University of Bristol participated in return for course credit (single testing = 36 participants[6]; group testing = 43 participants). Based on existing data from our lab suggesting an effect size of *dz* = 0.54 for comparison between targets with a 50% and 60% likelihood of being probed, we powered for a similar effect size of *d* = 0.5. This gave us at least an 80% chance of observing a similar effect size, with alpha set at .05, based on two-tailed tests, for each independent method of testing (i.e. single and group testing power calculations were calculated separately).

[5] The same qualitative pattern of results was observed when each experiment was analysed independently. When experiment was included as a between subject factor there were no reliable differences. Note, under a Bayesian framework combining the data is equivalent to multiplying the Bayes factors from each experiment (assuming the posterior from Experiment 1 is the prior for Experiment 2; see Ly, Etz, Marsman, Wagenmakers, 2018).

[6] Maria Antoniou and Veronika Hadjipanayi assisted with data collection.

Design. Target priority was manipulated in a within-subject design with five levels: very low (30), low (40), equal (50), high (60), very high (70), and reflected the true likelihood of a target being queried over the course of the whole experiment. The dependent variables were the same as in Experiment 1.

Procedure. The procedure was identical to that used in Experiment 1 apart from, when providing their response, participants had to indicate whether they thought they were tracking the queried target at the end of the trial or not by clicking the left mouse button for 'tracked' and the right mouse button for 'not tracked' (labels were put on the mouse buttons) [7]. This click also activated the response indicator line. Participants then used the same mouse button to finalise their response as detailed in Experiments 1. In the group testing experiment stimuli were presented in a 1,024 x 768 pixels window of a 21-inch LCD monitor (1920 x 1080 resolution) with a refresh rate of 60Hz.

2.4.2 Results and Discussion

Two participants were removed from the analysis because their overall magnitude of error was very high (and the model-based analysis suggested they had very high levels of guessing). The LME analysis and post-hoc comparisons used were identical to Experiment 1.

[7] We do not include analysis of this aspect of the design as so few participants actively engaged with it, but note the same qualitative pattern of results was observed when 'untracked' trials were excluded.

There was an effect of target priority on the magnitude of angular error, χ2 (2) = 121.49, $p < .001$, which decreased as target priority increased, $b = -0.467$, $SE = 0.04$, $t = 12.20$ (see Figure 2.3, left panel). Post-hoc tests showed no difference in the magnitude of angular error between the very low and low priority condition ($b = -0.13$, $t = 0.14$, $p = .639$). Magnitude of angular error was higher in the low compared with equal ($b = -0.90$, $t = 6.49$, $p < .001$), equal compared with high ($b = -0.29$, $t = 2.50$, $p = .049$), and high compared with very high priority conditions ($b = -0.42$, $t = 5.40$, $p < .001$), respectively.

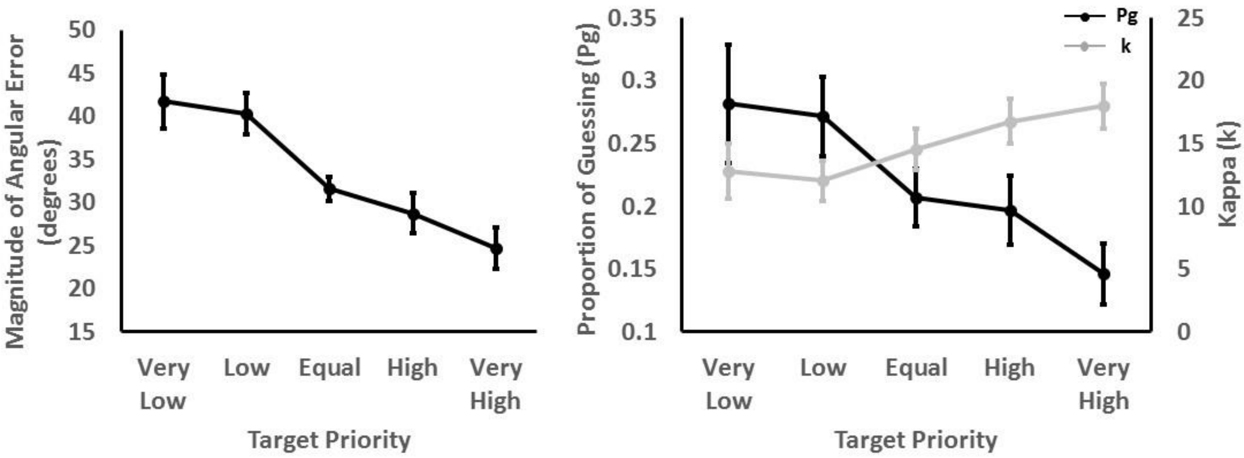


Figure 2.3. Mean error in magnitude of error, proportion of guessing and precision of tracking for each target priority in Experiment 2. Error bars represent 95% within-subject confidence intervals using Morey (2008).

Figure 2.4 shows the mixture model fits all the data combined for all participants, for each level of target priority. Fitting the models to each individual participant showed that there was an effect of priority on the proportion of guesses (P_g), χ2 (2) = 43.65, $p < .001$ (Figure 2.3, right panel). Participants demonstrated less guessing for higher priority targets, $b = -0.003$, $SE = 0.001$, $t = 6.85$. Post-hoc comparisons revealed no difference in the proportion of guessing between the very low and low priority targets ($b = -0.001$, $t = 0.39$, p

= .923). Proportion of guessing was higher for the low compared with equal priority targets (b = -0.006, t = 3.58, p = .003). However, there was no difference between the equal and high priority targets, (b = -0.001, t = 0.69, p = .787). Lower proportion of guessing was revealed in the very high compared with high priority condition (b = -0.005, t = 4.95, p < .001).

There was also evidence for an effect of target priority on the precision of representations κ, $\chi 2$ (2) = 27.59, p < .001, with precision increasing as target priority increased (b = 0.15, SE = 0.03, t = 5.18) (see Figure 2.3, right panel). There was no difference in precision between the very low and low, equal and high, and high and very high priority targets (t < 1.86, p > .184). There was, however, higher precision in the equal compared with low priority condition, b = 0.25, t = 0.11, p = .026.

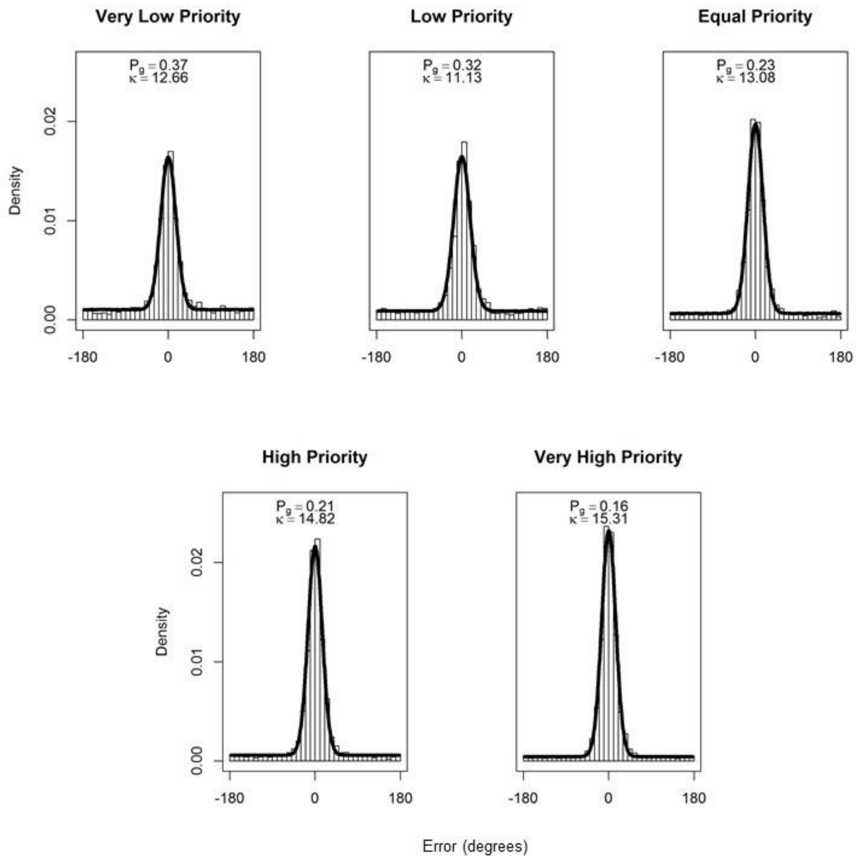


Figure 2.4. Mixture model fits for all participants for Experiment 2 for each level of target priority. The density plot displays the actual data and the black line shows the model fit. The proportion of guessing (P_G) and precision of tracking (κ_{VM}) parameters are also detailed.

In line with Experiment 1, the effect of target priority on the magnitude of angular error and proportion of guessing suggests that participants can split attention unequally. Specifically, more attention was allocated to the high priority target leading to a lower magnitude of error, and overall a lower proportion of guessing. Taken together, this result suggests flexible allocation of the attentional resource and, therefore, does not fit with pure slot-based accounts of attention allocation which would predict no effect of target priority because, under this account, each target is allocated a single slot.

Experiment 2 explored the extent to which attention splitting is fine-grained, namely the precision with which attention can be divided. There was some evidence for fine-grained spitting because there was a difference in magnitude of angular error and proportion of guessing for the high and very high targets. However, there was no evidence for a difference in these parameters between the very low and low priority targets. Since there was only limited evidence for fine-grained splitting, the results cannot distinguish between flexible and hybrid models of attention. No difference in tracking performance between the very low and low priority targets could be taken as evidence for a *slots + averaging* model of attention in which three and one slot(s) were allocated to the high and low priority target respectively, on any given trial thus resulting in the same pattern of results for the both the unequal splitting condition (i.e. high and low). However, better tracking performance in the very high compared with high pattern fits with a flexible or *slots + averaging* model which would predict a graded decrease in magnitude of angular error and proportion of guessing as target priority increases.

Experiments 1 and 2 demonstrated unequal attention splitting in a trajectory tracking task. Since position tracking does not automatically recruit trajectory tracking processing during MOT it has been suggested that position tracking may be a more primary representation during the process of tracking (Howard, Rollings, & Hardie, 2017). To further explore the extent to which unequal attention splitting was possible within a MOT-paradigm, we replicated Experiment 3 using a position tracking task. This was anticipated to provide more insight into the fine-grained nature of attention splitting.

2.5 Experiment3

Experiment 3 examined whether participants could allocate attention unequally using a different measure of tracking accuracy, to further generalise our findings. Tracking performance in Experiment 3 was indexed by the magnitude of spatial error from the correct final position of the queried target to the participant's reported final position of the queried target. More specifically, we used the x,y co-ordinates of the target's centre to index the actual final location and the x,y co-ordinates of the participant's click to index their position reports.

2.5.1 Method

Participants. Forty undergraduate students from the University of Bristol participated in return for course credit. Based on existing data from our lab suggesting an effect size of *dz* = 0.66 for comparison between targets with a 40% and 50% likelihood of being probed, we powered for a similar effect size of *d* = 0.5 which gave us at least an 80% chance of observing a similar effect size, with alpha set at .05 for two-tailed tests.

Design. Target priority was manipulated in a within-subject design with five levels: very low (30), low (40), equal (50), high (60), very high (70), and reflected the true probability of a target being queried over the course of the whole experiment. The dependent variable was the magnitude of error (pixels) from the correct final location of the queried target to the participant's reported final location of the queried target.

Procedure. The task was identical to that used in Experiment 2 (group participation condition) apart from the substitution of the trajectory tracking task with the position tracking task. Anaural prompt instructed participants to localise the target (i.e. click the location on the screen where they thought the centre of queried target with the priory stated through the headphones was) at the end of the movement. In the 50/50 conditions, the two targets were labelled with either an 'X' or 'Y' at the start of the trial and participants were cued at the end of the trial using these labels.

2.5.2 Results and Discussion

The LME analysis used was identical to Experiment 2. One participant was excluded from the analysis because their overall magnitude of error was very high (and the model-based analysis suggested they had very high levels of guessing). All trials on which the size of distance error was greater than 605 pixels was excluded. This value was chosen as it represented the 95th percentile of the data and the density plots showed less uniform responding thereafter.

There was an effect of target priority on the size of the distance error, χ2 (2) = 67.97, $p < .001$, with distance error decreasing as target priority increased, $b = -1.75$, $SE = 0.20$, $t = 8.91$. Post-hoc comparisons showed evidence for smaller distance errors in the high compared with equal condition, ($b = -1.67$, $t = 2.65$, $p = .040$), and equal compared with low priority condition ($b = -2.99$, $t = 3.80$, $p = .002$) (see Figure 2.5, left panel). There was also evidence for smaller error distances in the very high compared with high condition, ($b = -1.06$, $t = 3.10$, $p = .014$). There was no evidence for a difference in tracking error between the very low priority and the low priority condition, $b = -0.72$, $t = 1.31$, $p = .430$.

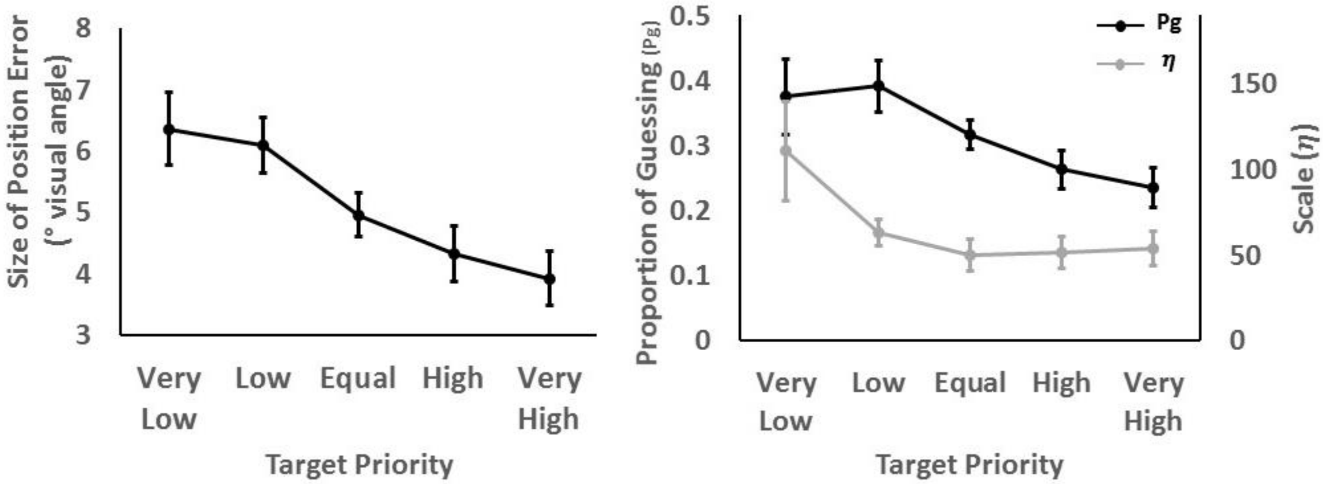


Figure 2.5. Mean error in size of position error, proportion of guessing and scale of distribution for each target priority in Experiment 3. Error bars represent 95% within-subject confidence intervals using Morey (2008).

In order to fit the data from Experiment 3, we used a different mixture distribution analysis because the error data distribution was linear and positively skewed. We used a Weibull distribution for the tracked items and a uniform distribution (from 0 to 605) for the guessing distribution. The dweibull function used in the analysis of is part of the base distribution package ‘stats’ (R Core Team, 2015). The Weibull has the advantage that both the shape and scale can vary, and can approximate other distributions, including the normal. The error distribution, ε, is therefore:

$$\varepsilon = P_G f_U(\mathrm{L} = 0, U = 605) + (1 - P_G) f_{WB}(\eta, \beta), \qquad (2)$$

in which P_g is the guessing rate, L and U are upper and lower bounds for the uniform distribution function f_U, and η and β are the scale and shape of the Weibull distribution function, f_{WB}. Figure 2.6 shows the mixture model fit to the combined data from all participant for each level of priority. As is evident in the plots, the scale parameter η is capturing the spread of the data, which we interpret as the precision of tracked items.

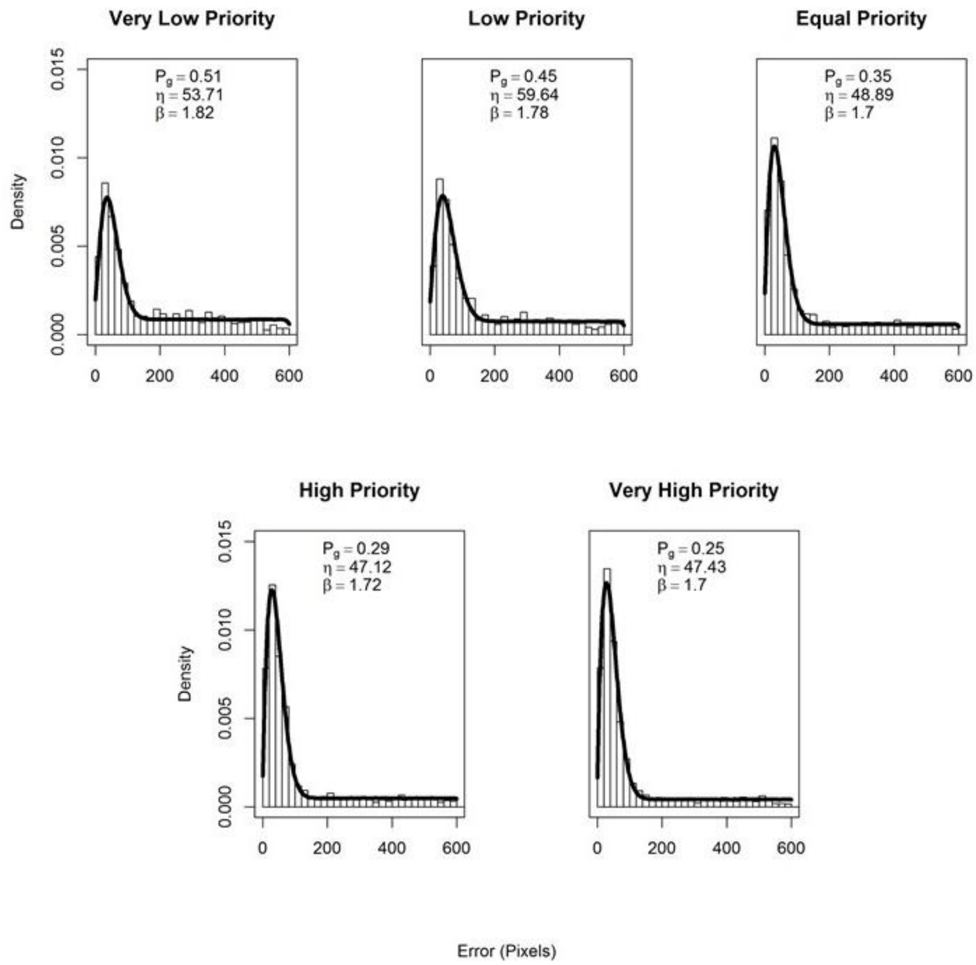


Figure 2.6. Mixture model fits for all data combined across participants for Experiment 3 for each level of target priority. The histogram plot displays the actual data and the black line shows the model fit. The proportion of guessing (P_G) precision of tracking (β the Weibull shape), and scale (η) parameters are also detailed.

There was an effect of priority on the proportion of guesses, χ2 (2) = 44.18, $p < .001$. Participants demonstrated less guessing for high priority targets, b = -0.004, SE = 0.001, t = 6.40 (see Figure 2.5, right panel). Post-hoc comparisons showed evidence for a lower proportion of guessing in the high compared with equal condition, (b = -.005, t = 4.87, p < .001), and equal compared with low priority condition, *(b* = -.007, t = 3.68, p < .003). There was also evidence for lower proportion of guessing in the very high compared with high condition, (b = -.0.003, t = 2.81, p = .027). There was, however, no evidence for a difference in the proportion of guessing between the very low priority and the low priority condition, b = .002, t = 0.51, p = .819.

There was no evidence for an effect of target priority on the shape, as measured by β, of representations, χ2 (2) = 0.71, p = .701. There was, however, evidence for an effect of target priority on scale, as measured by, η , χ2 (2) = 23.34, p < .001. As target priority increases, the distribution become more concentrated, b = 1.25, SE = 0.25, t = 5.02 (see Figure 2.5, right panel). Post-hoc comparisons revealed evidence for increased concentration for the low compared with very low priority condition, b = 4.79, t = 3.37, p = .007. There was greater concentration in the equal compared with low priority condition, b = -1.31, t = 2.75, p = .030, and high compared with equal, respectively, b = 0.17, t = 1.17, p = .004. The distribution for the very high compared with high priority targets was also more concentrated b = 0.22, t = 1.15, p < .001.

Overall, the position tracking task revealed evidence for unequal attention allocation which cannot be accounted for by fixed, slot-based models of attention. There was some evidence for more fine-grained attention allocation for the higher priority, with a smaller size of position error and lower proportion of guessing in the very high compared with high priority condition. There was, however, no evidence for fine-grained splitting for the lower priority targets (i.e. 30 vs 40). This pattern of results is similar to Experiment 2 with participants not differentiating between allocating their attention to a very low and low priority target.

2.6 General Discussion

In a series of three experiments, participants ability to split attention unequally between multiple moving objects was investigated. Results from all experiments revealed some evidence for unequal attention allocation according to strategic top-down control. This is in line with the existing literature documenting top-down, goal driven attention allocation in MOT (Brockhoff & Huff, 2016) and visual search (Jiang, Sha, & Remington, 2015). Such findings replicate research demonstrating unequal attention allocation during MOT in response to instructions, (Yantis, 1992; Cohen, et al., 2011) further supporting the efficacy of using goal-directed instructions to manipulate participants' attention allocation (Miller & Bonnel, 1994; Fitousi, 2016).

In Experiments 1, 2, and 3,, the proportion of guessing decreased as target priority increased. Guessing in response to a prompt to report one aspect of a target cannot be equated with a complete withdrawal of attention to all other aspects of that target, since for example, position and trajectory encoding for targets appear to be distinct processes (Howard, Rollings, & Hardie, 2017). Therefore, for any given modelled guessing response, this may not necessarily indicate a complete withdrawal of attention to that target if its trajectory (Experiments 1 and 2) or its position (Experiment 3) is not known. Even if the participant has completely withdrawn attention from a target, there are two possible reasons that could lead a participant to produce a guess response. They could drop the target (i.e. lose track of it) or swap the target (i.e. confuse it with a distractor). We propose that a combination of these events occur more frequently in the low priority condition than the high priority condition because less attention is allocated to the low priority target which constitutes unequal attention allocation. It could be argued that the increased proportion of guessing for low priority targets compared to high priority targets reflects participants' inability to split attention unequally. Specifically, participants may have dropped the low priority target on some trials and, therefore on those occasions, performed single object tracking which could be responsible for an increase in the precision for the high-priority target. This is unlikely because the guessing rate and magnitude of error is relatively low across all experiments and indicates non-guessing responses for the lower priority of targets on the majority of trials. Using electrophysiological markers and behavioural experiments, Drew, Horowitz, and Vogel (2013) distinguished between swapping and dropping trials. The relative frequency of these events is not distinguishable in the current data and, therefore, research using such measures within an unequal splitting MOT paradigm is required.

Experiments 1, 2, and 3 assessed how fine-grained unequal attention allocation is. The results from these experiments indicate that, on a given trial, participants can allocate more and less attention to the high and low priority targets, respectively. However, the results were less conclusive with regard to how fine-grained such attention splitting is.

There was some evidence for fine-grained splitting at higher levels of priority (e.g. between 60 and 70) but not at the lower end of the priority range (e.g., 30 and 40). Perhaps participants could not distinguish between what constitutes 30% and 40% of their attentional resource or were not sufficiently motivated by the task (participants were undergraduate students completing the experiment for course credit) to make the distinction, and so operated according to a binary 'more' or 'less' mechanism. Alternatively, it is possible that 30% of the attentional resource was sufficient to accurately track the very low priority targets and, therefore, the task was not sensitive enough to distinguish between highly similar target priorities. However, the effect of priority on proportion of guessing demonstrates that participants did guess on some trials and, therefore, 30% of the resource is not always sufficient. It is also important to recognise that the response procedure used in our experiments is different to the typical MOT literature in which participants must indicate whether a probed object is a target or non-target, which may have contributed to participants adopting different tracking strategies. However, trajectory and position tracking have been previously shown to be appropriate and sensitive measures of tracking performance which decline with set size (Horowitz & Cohen, 2010; Howard, Rollings & Hardie, 2017).

A persistent debate in the literature surrounds the structure of the attentional resource underlying tracking. Results from all experiments suggest that participants can split attention unequally indicating *some* flexibility to the attentional resource. This does not fit with fixed architecture theories of tracking which would predict that each target is allocated one slot, and, therefore, there would be no difference in tracking performance. Findings from Experiment 2 and Experiment 3 regarding the fine-grained nature of attention splitting are less conclusive. There is some evidence that participants may be able to only split according to a binary mechanism (i.e. high and low priority) which fits with *slots + averaging* models which assume that more than one slot can be allocated to a *high* priority target. In both the unequal attention splitting conditions (i.e. 30/70; 40/60) three slots and one slot can be allocated to a high and low priority target respectively and therefore no difference in tracking accuracy is observed. Under this account, no further precision in unequal splitting would be observed, since the slots cannot be subdivided any further, and therefore, this model explains the data presented here. Experiment 2 revealed evidence for a difference in magnitude of angular error and proportion of guessing which indicates fine-grained attention allocation. This fits with pure flexible and *slots + resources* models which predict a graded increase in tracking performance measures as target priority increases. Further research is needed to distinguish between these accounts.

Our results fit most closely with hybrid models of attention allocation. Pure flexible accounts require an additional assertion that not only can the resource be divided in a fine-grained manner, but that this fine-grained allocation of the resource can be divided out *unequally* between targets. A relevant analogy here might be the division of pay between workers: if forty units (dollars, euros, etc.) of currency are to be shared between four workers, the fixed account would suggest that there are four ten-unit notes which can be shared out, where a flexible account would suggest that there are in fact 4,000 subunits (e.g. cents) to be shared out. The flexible account asserts that this sum could be divided amongst 4,000 workers (actually an infinite number, but this requires subdivision of cents into electronic payments of less than one cent for the purpose of this analogy). However, the flexible account has so far been silent on whether or not this payment could be made unequally between workers, with some receiving more than others. The evidence we present here suggests that this is the case, that attention can be flexibly *and unequally* divided. How this unequal splitting of attention is achieved by the visual system does, however, warrant further theoretical consideration in the MOT literature.

The guessing rate remained relatively low throughout, indeed the mean guessing rate for the lowest priority targets across Experiments 2 and 3 was 29%. This is important because it suggests that on the majority of trials, participants did not appear to adopt the strategy of only single object tracking the high priority target, in which case we might expect nearer a 100% guess rate for the lower priority target. However, the results reported were averaged across trials and so it is possible that participants did not attempt to track *multiple* objects on each and every trial. Specifically, it is possible that participants engaged in single object tracking and used target priority to determine the number of trials on which they tracked *only* the high or low reward target. However, this is unlikely because there were only two targets which is below the proposed four object capacity limit for tracking. Whereas examining within-trial behaviour was not the main focus of this article, future research should focus on *how* participants achieve this unequal splitting. One way to directly investigate this would be by probing both targets at the end of a trial to gain insight into the relationship between tracking accuracy on the two simultaneously presented targets. A positive correlation between tracking performance would indicate that participants were engaging in multiple object tracking because performance on a given trial is broadly either *good* or *bad* for both targets. A negative correlation would indicate that participants were engaging in single object tracking because, as accuracy on one target (i.e. the tracked target) increases, accuracy on another target (i.e. the untracked target) decreases. No correlation between performance on the two targets might be consistent with participants attention fluctuating within a trial and, therefore, tracking a single object at the cost of another.

Although the studies presented indicate unequal attention allocation when performance is examined at the *trial level*, it is not possible to determine participants' attention allocation during the trial. It is possible that participants were tracking one target at a time but switched between targets during the trial, spending relatively more time on higher priority targets. Some have argued that attention is flexibly allocated in experiments investigating stimulus-driven unequal attention allocation (e.g. Iordanescu, Grabowecky, & Suzuki, 2009). Therefore, it is possible that prioritisation and unequal attention allocation only occurs when, for example, tracking becomes difficult such as in response to reduced inter-object spacing (Meyerhoff, Schwan, & Huff, 2018). Future research is therefore required to examine how attention is allocated at different points within a trial. One possible avenue is to use a dot probe detection task (e.g. Meyerhoff, Schwan, & Huff, 2018) in which probes are randomly presented within the tracking phase or two lateralised tracking areas are utilised to index attention allocation at different timepoints in a trial. Such research would also provide detail into the interplay between stimulus-driven and goal-directed attentional mechanisms within MOT.

A further consideration of the tasks we have used, is that equal and unequal attention splitting are potentially different tasks. Traditional MOT tasks might best be characterised primarily as an equal attention splitting task, although some have argued for unequal attention splits and attention reallocation in MOT (e.g. Iordanescu, Grabowecky, &

Suzuki, 2009). The unequal attention splitting MOT task used in these experiments also has a MIT component because participants must assign a target priority (a form of identity) to each of the targets. Identity encoding is not automatic during MOT (Pylyshyn, 2004; Scholl & Pylyshyn, 1999) and has been shown to require resources (Cohen, Pinto, Howe & Horowitz, 2011), in part due to identity-location binding processes (Saiki, 2002; Oksama & Hyönä, 2008). Future research should examine whether attention can be divided unequally in a purer MOT paradigm that does not require identity-location bindings. For example, distinct tracking areas or 'cages' (e.g. Howard and Holcombe, 2008) could be presented on each trial and each tracking area would be associated with a certain likelihood of being probed. This design would not require participants to maintain identity-location bindings because there would only be one target in each tracking area with, for example, three distractors.

These data demonstrate that participants can split attention unequally in MOT tasks. These findings are not consistent with fixed, slot-based accounts of attention allocation. Pure flexible accounts could account for the results with the additional assumption that attention may be divided unequally between targets. Hybrid models, specifically the *slots + averaging* model, explains the data reported here without further assumptions because a single target can be allocated more than one slot when tracking is below capacity. There is, however, limited evidence that this ability is fine-grained. One possible explanation is that participants lacked motivation to fully engage with the task and/or could not gauge what 30% of the attentional resource constituted which resulted in them splitting their attention according to a binary mechanism. To overcome these limitations alternative methods of prioritisation (e.g. reward) are required. Reward-based systems (e.g. point scoring, financial incentives) are more intuitive and have been shown to increase participants' effort (e.g.

Friedman and Sunder, 1994; Roth, 1995, although see Bonner & Sprinkle, 2002, for a review of conflicting evidence). Chapter 3 therefore manipulated target-associated reward to examine its effect on tracking performance.

Chapter 3 Reward-based unequal attention allocation in position tracking

3.1 Chapter Summary

In three experiments, target associated reward was manipulated to examine the effect on tracking accuracy in a dual-target position tracking task. Reward was used to increase participants understanding of and engagement with the task, compared with Chapter 2. Experiment 4 queried participants on the final location of one target at the end of a given trial and revealed better tracking accuracy for higher compared with lower reward targets. Experiments 5 and 6 used a double-probe technique to explore the relationship in tracking accuracy between two targets. The final location of both targets was queried at the end of the trial to gain a measure of tracking accuracy for each target. A Tracking Accuracy Comparison (TAC) score was then obtained by calculating the difference in tracking accuracy between the two targets. Across both experiments, there was a main effect of reward, indexed by higher precision and lower magnitude of error and proportion of guessing for the high priority targets. This supports unequal attention splitting, indicating some flexibility to the attentional resource. Experiment 5 showed no effect of the splitting condition (i.e. unequal splitting versus equal splitting) on TAC scores but did reveal an effect of response order on tracking accuracy, with worse performance for the second response. To eliminate the effect of response order, Experiment 6 used a touch screen but there was still evidence for poorer tracking accuracy for the second response, highlighting the role of memory in tracking, and no evidence for an effect of splitting condition on TAC scores.

3.2 Introduction

Chapter 2 developed a novel MOT task to investigate unequal attention allocation. Across three experiments, using both trajectory- and position-tracking measures, results showed that the overall increase in tracking accuracy for higher priority targets was the result of a lower guessing rate and higher precision. These results provide insight into the nature of the attentional resource underlying tracking. Fixed theories suggest that there are a limited number of slots that support tracking (e.g. Pylyshyn, 1989) whereas flexible theories propose a continuous, flexible pool of resources (e.g. Alvarez & Franconeri 2007). Under a slot-based account, there should be no effect of priority on precision because a fixed number of slots are allocated to support tracking. Our results therefore fit more closely with flexible theories, that predict precision should increase as target priority increases. There was limited evidence for fine-grained splitting (i.e. unequal attention splitting at smaller differentials), which fits more closely with hybrid models of attention, which combine aspects of fixed and flexible models. *Slots + averaging* models argue that more than one slot can be allocated to a single target and could therefore explain the results as three slots and one slot being allocated to the low and high priority targets, respectively. Further research is needed to distinguish between these accounts.

It is possible that methodological limitations contributed to limited evidence for fine-grained splitting. Participants may not have understood the target priority instructions, not grasped the difference between 60% and 70% of one's attention, or lacked motivation to engage with the task (participants were undergraduate students completing the experiment for course credit). Using reward as a goal-directed prioritisation strategy overcomes these limitations because a point scoring system is more intuitive and monetary reward provides a motivation for performing well on the task.

Reward is a well-documented method for manipulating attention allocation (Anderson, 2013). Kiss, Driver, and Eimer (2009) examined the effect of reward on event-related potential signatures of visual selection. In a visual search task for colour singleton targets, two different colours were associated with high and low reward. Inverse efficiency (i.e. mean correct reaction time divided by the proportion of correct responses) was lower, indexing more efficient performance, for high-reward than for low-reward targets. Kristjánsson, Sigurjónsdóttir, and Driver (2010) examined the effect of reward on visual search performance and found higher search efficiency for high compared with low-reward targets. These studies show that reward can influence attention allocation.

Reward is commonly used in the dual-task performance literature to examine whether two tasks share a common resource (e.g. Alvarez et al., 2005; Craik, Govoni, Naveh-Benjamin & Anderson, 1996). The logic of this approach is that as the incentive to complete one task increases, the performance on the other task decreases if a shared resource is required. Morey, Cowan, Morey, and Rouder (2011) examined whether participants could choose the proportions of working memory (WM) resource to allocate to two tasks (i.e. one visual and one auditory) using a manipulation of financial payoffs. In one condition, there was a high reward for correct responses in one task and a low reward for the concurrent task. Results showed a trade-off between performance in the two tasks which indicates that WM could be flexibly divided between the two tasks in response to financial payoffs. A similar logic could be applied to the MOT literature to examine how the resource underlying tracking, could be shared unequally between two distinct objects. More specifically, as the incentive to track one target increases, would tracking accuracy for that target increase at the expense of tracking accuracy for the other target? If so, this would indicate that a shared resource is utilised to track both targets and that it can be flexibly divided between the targets. This study examined whether reward can motivate unequal attention distribution between simultaneously tracked objects in a MOT task. A reward structure was used in which each object was worth a different number of points and the highest scoring participants received immediate monetary rewards.

3.3 Experiment 4

Experiment 4 manipulated the amount of reward associated with a target to investigate whether participants could split their attention unequally between two moving objects in a reward-driven manner.

3.3.1 Method

Participants. Fifty-two undergraduate students from the University of Bristol participated in return for course credit (aged 18 – 35 years; 48 females, 4 males). Based on existing data from our lab suggesting an effect size of dz = 0.54 for comparison between targets with a 50% and 60% likelihood of being probed, this sample size gave us at least an 80% chance of observing a similar effect size, with alpha set at .05 for two-tailed tests.

Design. Reward was manipulated in a within-subject design with five levels: very low (30 points), low (40 points), equal (50 points), high (60 points), very high (70 points). The more points participants accumulated, the more likely they were to win a monetary prize. This reflected the number of points participants were awarded if they *correctly* localised a queried target. The dependent variable was tracking accuracy: the distance between the participant's response (the x,y position of the mouse cursor when participants clicked the left mouse button) and the queried target's centre. A successful localisation, in terms of rewarding the points to a participant, was defined as estimating the final location of the queried target within the diameter of the target's final location. Because participants would rarely get the exact centre point of an object's location, we reasoned that they would become demotivated unless we rewarded them for an approximately correct response.

Materials and Procedure. Stimuli were presented in a 1,024 x 768 pixel window on a 21-inch LCD monitor (1920 x 1080 resolution) with a refresh rate of 60 Hz.

The position tracking task was used. At the start of a trial, each target had a value (i.e. 30, 40, 60, 70) presented on it denoting the number of points that would be awarded for successfully tracking that target (in all conditions the rewards totalled 100). In the 50-50 condition, participants were instructed to split their attention equally between the two targets. In the 50/50 condition, an 'X' or 'Y' was presented instead of a numerical value to distinguish between the two objects at test. The disc representing the participants estimated final location of the target was also shown coloured green (i.e. scored the number of points associated with that target) or red (i.e. did not score points) depending on whether selected coordinates fell within the circumference of the target or not.

Participants were told that the aim of the task was to score the highest number of points. They were clearly instructed to not try and *only* track the most rewarded target (i.e. avoid single object tracking). Participants were told that there was a monetary reward for the highest (£15) and second highest (£10) scoring participant. Participants were tested in one of two group testing sessions, used to further motivate participants to engage in the task by introducing a competitive element (i.e. the highest performing participants in a given session received the monetary prizes). Participants completed 10 practice trials to familiarise themselves with the task, followed by 250 experiments trials, the order of which was randomised across 10 blocks. The experiment lasted approximately 1 hour.

3.3.2 Results and Discussion

Two participants were removed due to very high average errors and the mixture model analysis suggesting they were guessing on a disproportionate number of trials. LME analysis was used. Target reward was entered into the model as a fixed effect. As random effects, there was a random intercept for subjects and a by-subject random slope for the effect of target reward.

There was a main effect of reward on magnitude of position error, $\chi 2\ (2) = 49.06$, $p < .001$, whereby the magnitude of position error decreased as target reward increased, $b = -1.30$, $SE = 0.17$, $t = 7.46$ (see Figure 3.1, left panel). Post-hoc comparisons showed that there was no difference in the size of error between either the very low and low reward targets ($b = 0.74$, $t = 1.47$, $p = .175$), or the low and equal reward targets ($b = -1.49$, $t = 2.00$, $p = .147$). Position errors were, however, smaller in the high priority condition compared with the equal reward condition (*b* = -3.27, *t* = 5.85, *p* < .001). However, no differences were revealed between the high and very high reward condition (*b* = -0.09, *t* = 0.20, *p* = .190).

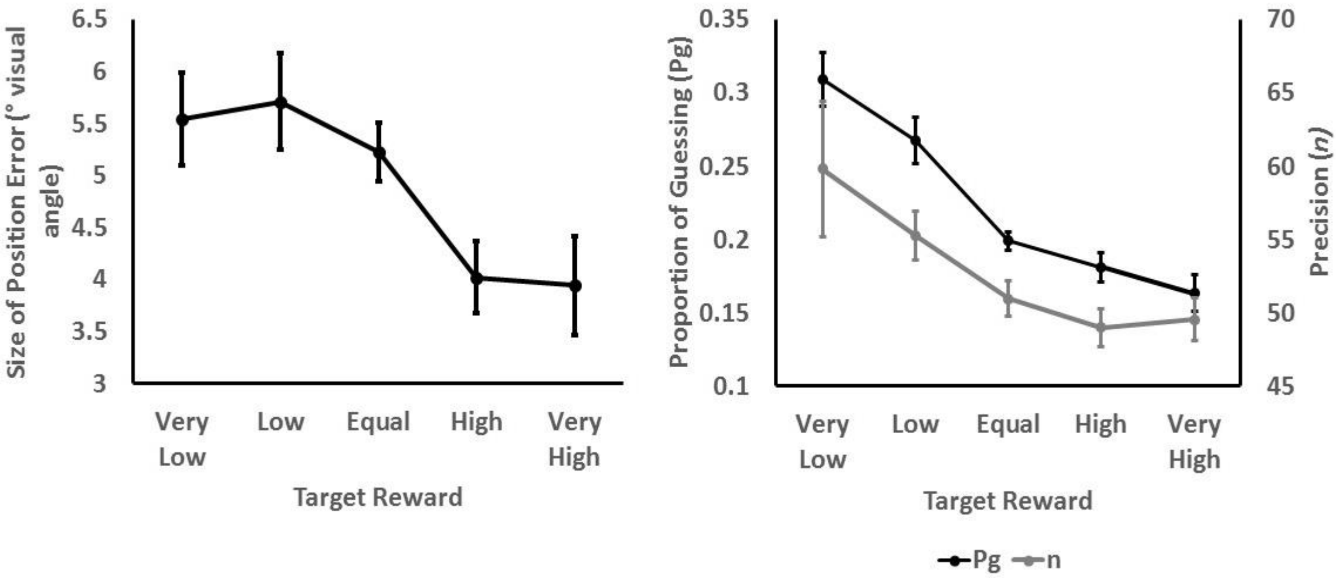


Figure 3.1. Mean error in size of position error, proportion of guessing (black line) and scale (grey line) of distribution for each target priority in Experiment 4. Error bars represent 95% within-subject confidence intervals following Morey (2008).

Following Chapter 2, in order to estimate the guessing rate and precision parameters from the data, a mixture of a Weibull distribution (using the dweibull function, R Core Team, 2015), for the tracked items error distribution (because the error data distribution was linear and positively skewed) and a uniform distribution (from 0 to 559 pixels, 559 pixels represented the 95th percentile of the error distribution) for the guessing distribution (see Chapter 2, for a detailed explanation and justification of distributions) was fitted. The Weibull has the advantage that both the shape and scale can vary, and can approximate other distributions, including the normal. The scale parameter η captures the spread of the data, which we interpret as the precision of tracked items.

There was a main effect of reward on the proportion of guessing, $\chi 2$ (2) = 68.04, $p <$ .001, whereby the proportion of guessing decreased as target reward increased, b = -0.004, SE = 0.004, t = 8.74 (see Figure 3.1, right panel, black line). Post-hoc comparisons showed that there was no difference in the proportion of guessing between the very low and low reward targets (b = -0.004, t = 1.87, p = .186). However, there was evidence for a lower proportion of guessing in the equal compared with low reward (b = -0.008, t = 4.27, $p <$ .001), high compared with equal (b = -0.002, t = 3.09, p = .003), and high compared with very high reward targets (b = -0.001, t = 1.81, p = .029).

There was evidence for an effect of target priority on precision, as measured by η, $\chi 2$ (2) = 9.21, $p <$ .001. As target reward increased the distribution became more concentrated, reflecting greater precision, b = -0.21, SE = 0.07, t = 3.07 (see Figure 3.1, right panel, grey line). Post-hoc comparisons showed no difference in precision between the very low and low reward targets (b = -0.29, t = 0.60, p = .836). There was evidence for increased concentration for the equal compared with the low (b = 0.36, t = 3.23, p = .009) and the high compared with the equal reward conditions (b = 0.19, t = 0.05, p = .002). There was no difference between the high and the very high reward conditions (b = 0.06, t = 0.68, p = .170).

These results suggest that participants can allocate more and less attention to a *high* and *low* priority target, respectively, but there was limited evidence for fine-grained splitting. Although it is unlikely that participants struggled to understand the points scoring system, it is possible that the reward manipulation was still not sufficient to motivate participants to fully engage with the task. Some participants may have split according to a binary high versus low strategy thus highlighting the role that strategy might exert on performance. Although the results are consistent with the interpretation that participants split attention unequally on each individual trial, we cannot rule out the possibility that participants split attention unequally across trials. Participants could have engaged in single object tracking on each trial and used reward to determine the number of trials on which they tracked *only* the high or low reward target. Alternatively, it could be argued that participants sometimes *dropped* a target (i.e. lost the target completely) and, on these occasions, performed single object tracking only. This criticism also applied to Chapter 2 whereby participants may have probability matched across trials, and simply stopped tracking the low priority targets altogether. This is unlikely because the proportion of guessing remained low for all target rewards and there was a relatively good level of tracking accuracy, but our previous experiments cannot conclusively rule out this strategy. Experiment 5 therefore used a double-probe response procedure in which the final position of both targets was queried at the end of a given trial.

3.4 Experiment 5

Experiment 5 used a double-probe procedure to compare the relationship between tracking accuracy for two targets in a given trial and gain further insight into the extent to which participants can split their attention unequally between two moving targets. We obtained a Tracking Accuracy Comparison (TAC) score to quantify the difference in tracking accuracy between two targets. We hypothesised that the more unequal the attention split, the greater the TAC score would be. In equal splitting trials, we predicted that there would be no difference in TAC score because participants would allocate the same *amount* of the attentional resource to both targets. In contrast, on unequal splitting trials, participants would allocate *more* attention to a high priority target resulting in a larger TAC score. To our knowledge, only Howard and Holcombe (2008) have used a double-probe procedure previously, although they used it to distinguish between the role of parallel and serial processing within MOT.

3.4.1 Method

Participants. Fifty-seven undergraduate students from the University of Bristol participated in return for course credit (aged 18 – 35 years; 43 females, 14 males). Based on existing data from our lab suggesting an effect size of *dz* = 0.66 for comparison between targets with a 40% and 50% likelihood of being probed, this sample size gave us at least an 80% chance of observing a similar effect size of *dz* = 0.5, with alpha set at .05 for two-tailed tests.

Design. Splitting condition was manipulated in a within-subject design with three levels: equal splitting (50:50), small unequal splitting (60:40), large unequal spitting (70:30). The double-probe procedure allowed us to examine within-trial behaviour. The primary dependent variable was a TAC measure. At the end of a trial, the final location of both targets was queried. Tracking accuracy for each target was obtained by calculating the distance between the participant's response and the queried target's centre. A TAC score was then obtained by calculating the difference in tracking accuracy between the two targets presented in the same trial.

Materials and Procedure. The task and monetary incentives were identical to Experiment 4 except for the method of denoting an equal-splitting trial. For all splitting conditions (i.e.

now including the equal-splitting trial), the number of points (i.e. 30, 40, 50, 60, 70) awarded for successfully localising a given target was presented. The response procedure required participants to localise both targets. Participants chose the order in which they localised the targets. Participants completed 10 practice trials, followed by 120 experimental trials across 6 blocks. The total testing time was approximately 30 minutes.

3.4.2 Results and Discussion

We conducted similar LME analysis as Experiment 4, but with splitting condition (small, equal, large) entered into the model as a fixed effect. Regarding random effects, there was a random intercept for subjects and a by-subject random slope for the effect of splitting condition.

There was no effect of splitting condition on TAC score, $\chi2$ (2) = 0.18, p = .912. Since this did not fit with our hypothesis, we conducted an exploratory LME analysis investigating whether there was an effect of the order of response on the size of position error. A model including a fixed effect of response order, fixed effect of target priority, a fixed response order*target reward interaction and a by-subject random slope in target reward was the best fit to the data. There was a main effect of reward (t = 3.84, p < .001), with a decrease in error with an increase in reward. There was also a main effect of response order (t = 0.70, p < .001), with larger errors for the second response. There was also an interaction (t = 2.94, p < .001), with a larger effect of response order observed for the more highly rewarded target (see Figure 3.2). Indeed when very high rewarded objects were responded to second, error rates were relatively high, counter to our expectations.

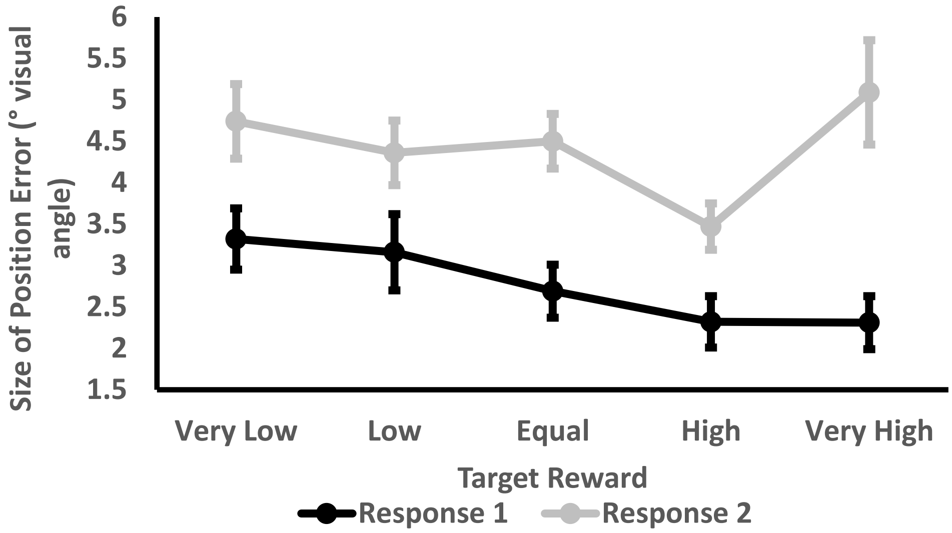


Figure 3.2. Mean error in size of position error for the first and second response in Experiment 5. Error bars represent 95% within-subject confidence intervals following Morey (2008).

To investigate the proportion of guessing and precision of tracking for Response 1 and Response 2, we used the same mixture distribution as in Experiment 5. The uniform distribution ranged from 0 – 438 pixels (i.e. 95th percentile for size of position error). It was not suitable to use this analysis to look at the effect of target reward for each order of response because each participant chose the order in which they responded and, therefore, there are very different numbers of data points in each response order for each level of reward for each participant. Moreover, due to the interaction between target reward and response order, it is not appropriate to collapse over response order. A paired samples *t-test* showed that the proportion of guessing was higher for Response 2 (M = 0.17, SD = 0.14) than Response 1 (M = 0.09, SD = 0.07), $t(56) = 4.45$, $p < .001$, $d = 0.66$. There was also evidence for lower precision, indexed by the scale parameter, η, for Response 2 (M = 62.32, SD = 16.40) than Response 1 (M = 45.68, SD = 9.44), $t(56) = 8.95$, $p < .001$, $d = 1.17$.

Figure 3.3 shows a scatterplot relating error magnitudes for the higher (60 and 70) and lower (30 and 40) reward targets on a given trial. We ran a correlation analysis to examine the within-trial performance to provide insight into attention splitting on any given trial. In line with Howard and Holcombe (2008), data were normalised such that the mean of the dataset for each participant was zero. There was no significant correlation between error magnitudes for the higher and lower priority targets (correlation coefficient = -0.002 with 95% confidence intervals ± 0.029, N = 4,560, p = .868). The absence of a correlation is consistent with no relationship between tracking accuracy on the high and low priority target, respectively, on a given trial. This also suggests that, on most trials, participants did not engage in single object tracking, which would predict a strong negative correlation (i.e. as tracking accuracy on Target 1 increases, tracking accuracy on Target 2 decreases). Nevertheless, Figure 3.3 shows that, on some trials, participants could have engaged in single object tracking indicated by the L-shaped scatterplot, with each 'arm' representing a trial where tracking accuracy was high for one target and low for the other.

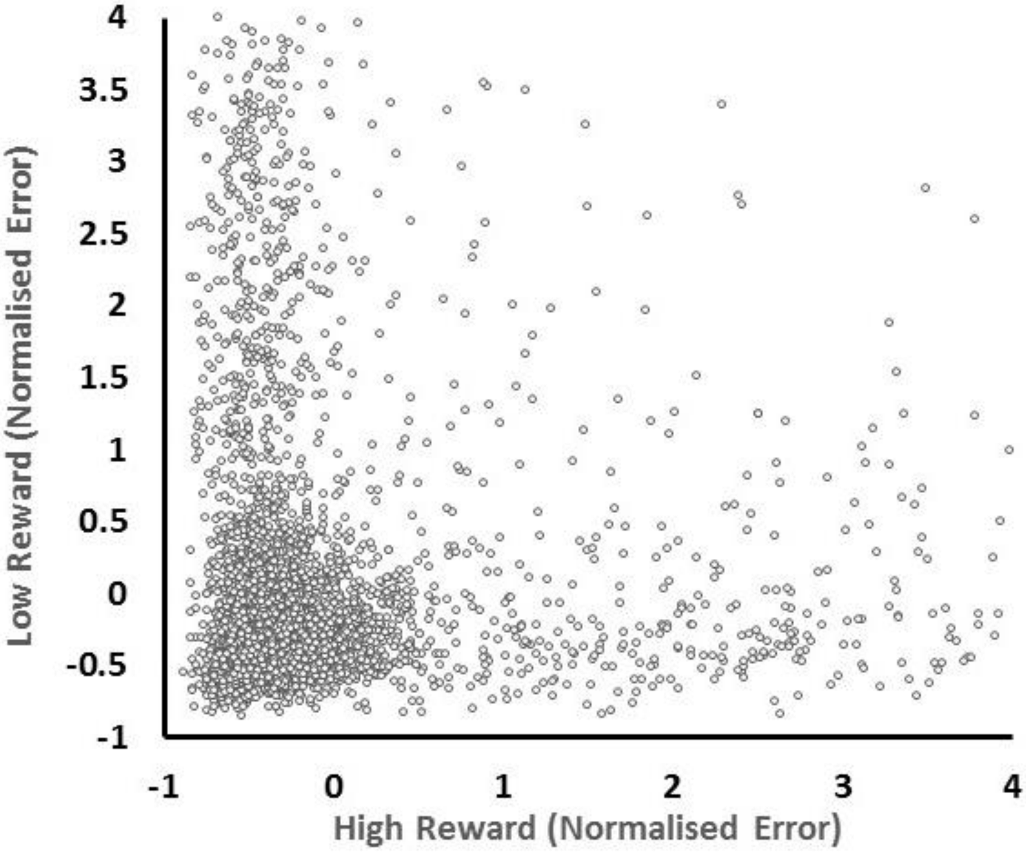


Figure 3.3. Normalised errors in reporting the final location of the high and low reward target on a given trial in Experiment 5.

Planned analysis revealed no effect of splitting condition on TAC and no correlation in the size of position error between the lower and higher reward targets. Since these findings contradict our hypothesis, we conducted exploratory analysis which revealed that response order introduced noise to the experiment, with the size of position error being larger for the second response. Interestingly, there was an effect of reward in this analysis, with a decrease in size in position error as target reward increased. The mixture modelling further supported this, with participants displaying a higher guessing rate and lower precision for the second response. This finding fits with that Howard and Holcombe (2008) who reported smaller error magnitudes for the first response compared with the second response. Because participants could choose which target they responded to first, it is possible they selected the target they were most confident with first (in order to maximise reward). However, it is also possible that participant's representation for the second target's location degraded (either through memory decay or interference from the first response). In order to reduce the effects of memory decay by reducing the difference in response times (and any resulting performance decrements), Experiment 6 used a touch screen, allowing participants to respond more rapidly to both targets.

3.5 Experiment 6

3.5.1 Method

Participants. Twenty-eight undergraduate and postgraduate students from the University of Bristol volunteered or participated in return for course credit (aged 18 – 35 years; 21 females, 7 males). Based on existing data from our lab suggesting an average effect size of *dz* = 0.55 for comparison between targets with 50 points reward and 60 points reward, we required a sample size of 28 to achieve 80% power at an alpha of .05 to replicate this effect.

Design. The design was identical to Experiment 5.

Task and Procedure. The task and procedure were identical to Experiment 5 apart from participants gave their response using a 17" 3M M170 MicroTouch TFT touch screen monitor. Participants were instructed to rest their fingertips on two markers on the bottom left- and right-hand side of the screen in between-responding. The experimenter ensured compliance with this component of the task by watching participants as they completed the task. This was to ensure participants were not tracking the targets with their fingers and reduce the time between a trial ending and participants pressing the screen.

3.5.2 Results and Discussion

The analysis was identical to Experiment 5. There was no effect of splitting condition on TAC scores, χ2 (2) = 4.08, *p* = .130. We therefore conducted an exploratory LME analysis to investigate whether the effect of response order persisted. A model including a fixed effect of response order, fixed effect of target priority, a fixed response order x target reward interaction and a by-subject random slope in target reward was the best fit to the data. There was a main effect of reward (*t* = 2.38, *p* = .018), with a decrease in size of position error for the high reward targets (see Figure 3.4). There was also a main effect of response order (*t* = 2.32, *p* = .021), with larger position errors for the second response (See Figure 3.4). There was, however, no evidence for an interaction, showing that the same overall pattern of results was observed for both first and second response.

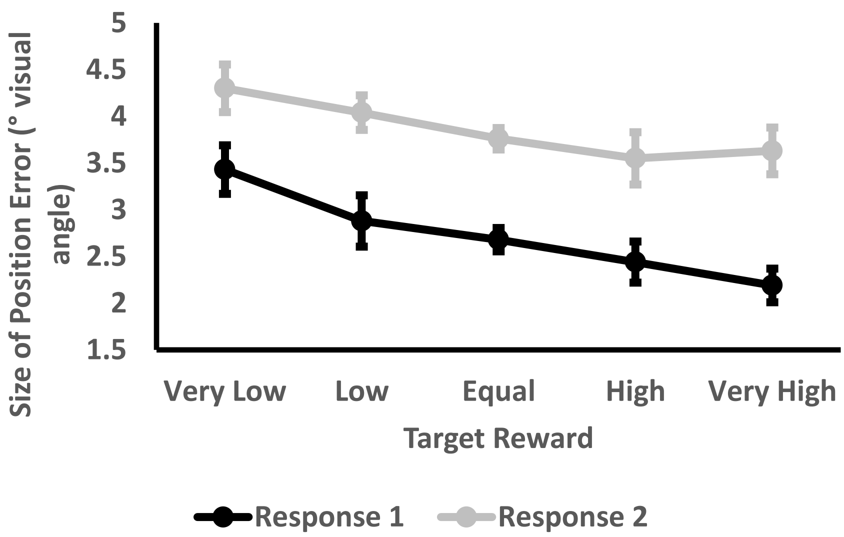


Figure 3.4. Mean error in size of position error for Response 1 and Response 2 in Experiment 6. Error bars represent 95% within-subject confidence intervals using Morey (2008).

Since there was no interaction between response order and reward in Experiment 6, we collapsed across response order to allow investigation into the effect of reward on proportion of guessing and precision of tracking. The LME analysis was identical to Experiment 4. The uniform distribution ranged from 0 – 393 pixels (i.e. 95^{th} percentile for size of position error). There was a main effect of reward on the proportion of guessing, $\chi2$ (2) = 8.67, *p* = .013, whereby the proportion of guessing decreased as target reward increased, *b* = -0.001, *SE* = 0.00, *t* = 3.02 (see Figure 3.5). Post-hoc comparisons showed that there was no difference in the proportion of guessing between the very low and low reward targets (*b* = -0.000, *t* = 0.04, *p* = .660). There was also no evidence for a lower proportion of guessing in the equal compared with low reward (*b* = -0.002, *t* = 0.83, *p* = .711). There was significant difference in precision for the high compared with equal (*b* = -0.002, *t* = 2.92, *p* = .024), and high compared with very high reward targets (*b* = -0.002, *t* = 2.58, *p* = .050).

There was evidence for an effect of target priority on precision, as measured by η, $\chi2$ (2) = 26.50, $p < .001$. As target reward increased the distribution became more concentrated, reflecting greater precision, $b = -0.18$, $SE = 0.07$, $t = 2.52$ (see Figure 3.5, right panel, grey line). Post-hoc comparisons showed no difference in precision between the very low and low reward targets ($b = -0.16$, $t = 1.07$, $p = .570$). There was no evidence for increased concentration for the equal compared with low ($b = -0.33$, $t = 1.61$, $p = .291$). There was limited evidence for increased concentration for the high compared with equal reward conditions ($b = -0.15$, $t = 2.51$, $p = .059$). There was no difference between the high and very high reward conditions ($b = -0.03$, $t = 0.89$, $p = .676$).

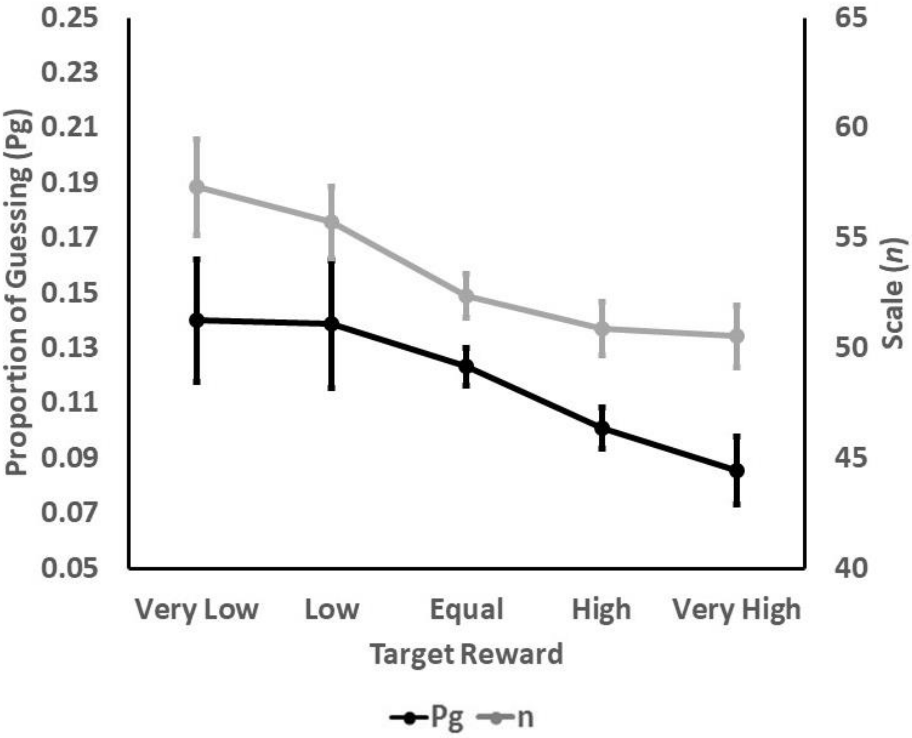


Figure 3.5. Mean proportion of guessing and scale of distribution for each target reward in Experiment 6. Error bars represent 95% within-subject confidence intervals using Morey (2008).

To investigate the proportion of guessing and precision of tracking for Response 1 and Response 2, we used the same mixture distribution as in Experiment 5. The uniform distribution for this analysis also ranged from 0 – 393 pixels (i.e. 95th percentile for size of position error). A paired samples *t-test* showed that the proportion of guessing was higher for Response 2 (*M* = 0.15, *SD* = 0.17) compared with Response 1 (*M* = 0.07, *SD* = 0.08), *t*(27) = 4.07, *p* < .001, *d* = 0.54. There was also evidence for lower precision, indexed by the scale parameter, η, for Response 2 (*M* = 62.70, *SD* = 18.67) than Response 1 (*M* = 45.68, *SD* = 9.21), *t*(27) = 6.41, *p* < .001, *d* = 1.05. This analysis further confirms the strong effect of response order on both the proportion of guessing and precision of tracking.

Figure 3.6 shows a scatterplot relating error magnitudes for the high and low priority targets on a given trial. We ran the same correlation analysis as Experiment 5. There was no significant correlation between the high and low priority targets (correlation coefficient = -0.008 with 95% confidence intervals ± 0.041, *N* = 2,240, *p* = .693).

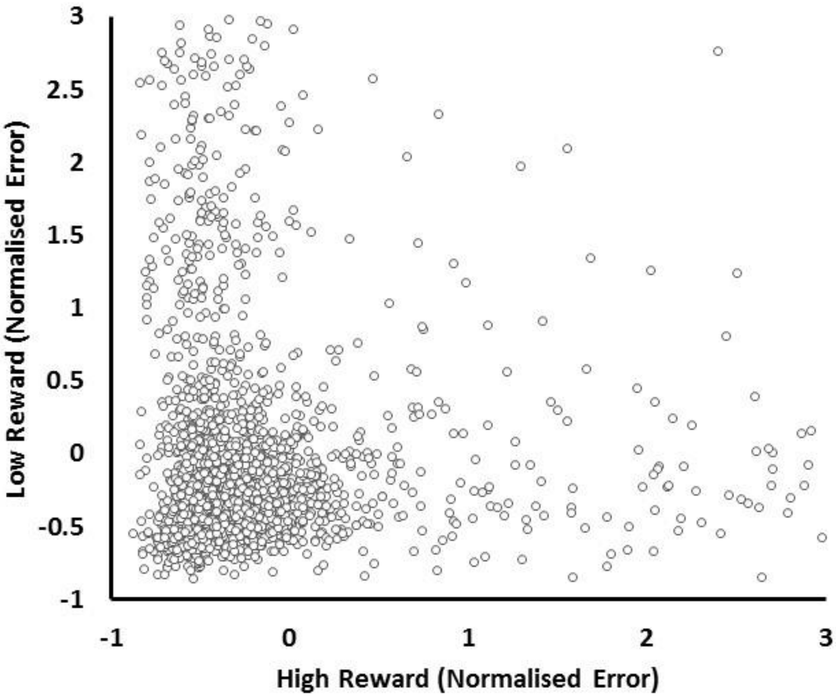


Figure 3.6. Normalised errors in reporting the final location of the high and low reward target on a given trial in Experiment 6.

3.6 General Discussion

In three experiments, we manipulated target-associated reward to investigate whether participants could split attention unequally. Position tracking was more accurate for high compared with low reward targets, indexed by smaller size of position errors, higher precision and a lower proportion of guessing. This demonstrates unequal attention allocation but there was no evidence for fine-grained attention splitting. These findings are in line with Chapter 2, which demonstrated unequal attention allocation driven by target priority. Moreover, we demonstrated the efficacy of using reward to induce unequal attention splitting, in line with the working memory literature (Morey et al., 2011).

Experiment 4 used a standard position-tracking task in which participants reported the final position of a queried target. Results showed that participants' tracking performance was better for the high, compared with low reward targets, indexed by smaller size of position errors, higher precision and a lower proportion of guessing. It could be argued that the high proportion of guessing and low precision revealed for the low priority target reflects participants' inability to allocate attention unequally and, instead, participants were engaging in single object tracking. In line with Chapter 2, this is unlikely since the guessing rate remains relatively low across all target rewards. However, a limitation of the response procedure used in Experiment 4, and most published MOT research, is that participants are queried about the status or characteristics of only one object. This method provides no insight into the relationship between performance on two targets presented simultaneously on a given trial.

To gain insight into the relationship between performance on two targets presented simultaneously on a given trial, Experiments 5 and 6 used a double-probe procedure in which both targets were queried at the end of a given trial. We hypothesised that there would be an effect of the splitting condition on TAC. On equal splitting trials, we predicted that participants would allocate the same *amount* of attention to each target and, therefore, there would be a very small difference in tracking accuracy (i.e. a baseline). In contrast, when participants split their attention unequally, there would be a difference in tracking accuracy between the two targets. Specifically, in the 70-30 condition (i.e. large unequal split) we expected a larger difference in tracking accuracy than in the 60-40 condition. Experiment 5 revealed no effect of splitting condition on the difference in tracking accuracy. Exploratory analysis revealed that there was an effect of response order on the size of position error, proportion of guessing and precision of a response. Specifically, participants performed worse when localising the second target. Although Experiment 6 used a touch screen to reduce memory decay, a similar pattern of results was observed.

The results, from Experiment 5 and 6, show that response order affected tracking accuracy, indexed by size of position error, precision, and proportion of guessing. Howard and Holcombe (2008) reasoned that different sources of imprecision would increase errors in both the first and second reported targets. Specifically, during the first report, participants must hold in memory the location of another target which could lead to interference. During the second report, participants must hold the location in memory for a longer period of time which could lead to decay due to the time delay or interference from thinking about and responding to the first target. Thornton and colleagues (2014, 2015) developed an interactive MOT (iMOT) task and showed that executing a motor action relevant to the display did not impair tracking performance which suggests it is unlikely that the motor response contributed to poorer performance for the second response (although they used a different paradigm). Tripathy and Barrett (2004) developed a multiple trajectory tracking (MTT) task in which participants were required to monitor the trajectories of dots to detect deviations from linear trajectories and showed that performance dropped significantly when participants had to track two or more dots. Narasimhan, Tripathy, and Barrett (2009) showed a set-size effect in an MTT task, with a decrease in accuracy as the number of distractor trajectories increased. Since participants had to retrieve the first half of the trajectory to detect any deviations, Narasimhan, Tripathy, and Barrett (2009) suggested that poor tracking accuracy could be due to memory decay for the earlier trajectory. Introducing a delay of 400 ms between the first and second half of trajectories also resulted in poorer performance which further highlights a role of memory in MTT (Narasimhan, Tripathy, & Barrett, 2009). In subsequent work, Shooner, Tripathy, Bedell, and Öğmen (2010) used a direction-report MOT task in which participants had to report the direction of motion of a target after a brief delay. As time delay increased, there was a decrease in performance, further demonstrating a clear contribution of memory to MOT. Our results, demonstrating poorer performance for the second response, further implicate a role of memory within tracking.

In Experiment 6, although participants could respond quicker, and in fact almost simultaneously (they could move both index fingers over both targets simultaneously), using the touch screen, the effect of response order remained. This finding has implications for real-world occupations. Traditional MOT tasks are atypical of the real world in which individuals distribute attention to objects in different locations within the visual field (i.e.

not just within a single computer screen). For example, in CCTV monitoring, attention must be allocated to several screens in distinct spatial locations, each with multiple moving objects on a given screen (e.g. 4 people). Since our results suggest that participants' memory of the precise location of a given object decreases quickly, more research understanding the effect of time on memory decay within a MOT-like framework is required from both a theoretical and practical perspective.

Using the double-probe procedure enabled an investigation into the correlations between tracking accuracy on two targets presented simultaneously on a given trial. These analyses can provide insight into the role of serial versus parallel processing in tracking. Howard and Holcombe (2008) hypothesised that a negative correlation would support serial processing because, at a given time, attention is allocated to one target. In contrast, parallel processing accounts predict a positive correlation because attention is shared across targets simultaneously and therefore performance fluctuates across trials due to changes in general arousal. In line with Howard and Holcombe (2008), Experiment 5 and 6 revealed no evidence for a correlation suggesting that either a weaker form of serial processing or a combination of parallel and serial processing is used to support multiple object tracking.

It is important to acknowledge that, due to the reward manipulation in this task, participants may have adopted different strategies to maximise reward. For example, on trials in which one target was lost during tracking, participants may have made two responses close to the target they were successfully tracking in order to ensure they scored those points. Understanding the relationship between reward and decision-making, namely choosing a strategy one believes will result in maximum reward, is an interesting avenue for further research in the MOT literature. Research has previously used eye-movements as an indicator for decision-making processes within a reward framework (Stritzke, Trommershäuser, & Gegenfurtner, 2009) which could be applied to the MOT literature to provide insight into the strategies adopted by participants by gaining insight into their scanning patterns both across- and within- trials. Alternatively, participants could be queried about any strategies that they used after completion of the experiment.

There is a continuing debate regarding the nature of the attentional resource underlying tracking. Our results largely replicate Chapter 2 and, therefore, provide support for a *slots + averaging* hybrid model of attention. There is evidence that participants can split attention unequally because there is a difference in tracking accuracy between the low and high priority targets which indicates flexibility to the attentional resource. However, there was limited evidence for fine-grained splitting which does not fit with pure flexible models of attention. We argue that the results could represent participants allocating one and three slots to the low and high priority target, respectively (i.e. *slots + averaging* models) which results in limited evidence for fine-grained splitting. However, further experiments, which preclude such a 3:1 split will be needed to further test the validity of the *slots + averaging* model.

Three experiments demonstrate participants' ability to split attention unequally between two objects in a position-tracking task. Models of MOT must incorporate these findings which indicate a flexible component to attention allocation during tracking. We add to the limited literature using position tracking to index tracking accuracy within MOT frameworks and re-introduce the double-probe procedure (to our knowledge only Howard

& Holcombe, 2008, have used this to date in the tracking literature) which enables investigation into the relationship between tracking accuracy on two targets simultaneously presented. Experiments 5 and 6 highlight that the order with which participants respond to a target affects accuracy, and possibly the speed with which the spatial representation of a target decays. Further studies will be needed to disentangle to role of temporal decay and response interference in the response-order effect, which has both practical and theoretical implications.

Chapter 4 No evidence for attentional narrowing within a MOT framework

4.1 Chapter Summary

Chapter 4 investigated the effect of state anxiety on unequal attention splitting in an attempt to further distinguish between fixed and flexible accounts of attention allocation. Specifically the theory of attentional narrowing, which suggests that the attentional window narrows in anxiety-provoking situations, was tested. Attentional narrowing predicts that, under anxiety, participants would allocate more and less attention to the high and low target, respectively, in the unequal attention splitting MOT task. Experiment 7 aimed to induce cognitive anxiety, but the manipulation checks showed that it was unsuccessful. Therefore, Experiment 8 used a physiological anxiety induction technique, the 7.5% CO_2 challenge model, which was deemed successful at inducing anxiety. However, there was no evidence for attentional narrowing. Therefore, these experiments cannot further differentiate fixed and flexible accounts of tracking beyond Chapters 2 and 3.

4.2 Introduction

MOT is commonly undertaken in occupations performed in pressurised and anxiety-provoking environments such as the military, air traffic control, and sports. Morelli and Burton (2009) showed poorer MOT performance when participants viewed anxiety-inducing photographs compared to those who viewed neutral photographs, and Prinet and Sarter (2015) revealed a decrease in performance in a simplified air traffic control task (i.e. involved a tracking component) in anxiety-provoking situations. However, to date, no other research has investigated the effect of state anxiety[8] on MOT, which highlights a paucity of data given the prevalence of occupations that require MOT, and are undertaken in anxiety-provoking situations. Moreover, investigating the influence of anxiety on unequal attention spitting has the potential to inform the debate regarding the nature of the attentional resource that underlies MOT.

Pressure, which refers to any factors that increase the importance of performing well, leads to the emotional state of the anxiety (Baumeister, 1984). Multidimensional models of anxiety distinguish between two components of anxiety: somatic and cognitive (Martens, Vealey, & Burton, 1990). Physiological anxiety[9] refers to the physical symptoms of anxiety (e.g. increased heart rate, sweating, 'butterflies') whilst cognitive anxiety describes the emotions that characterise anxieties such as worry and apprehension (Krane, 1994; Martens, Vealey, & Burton, 1990). Spielberger, Gorsuch, Lushene, Vagg, and Jacobs (1983) distinguished between two types of anxiety: trait and state. Trait anxiety refers to a more

[8] For the remainder of the chapter, anxiety is taken to mean state anxiety. When trait anxiety is being discussed, it will be fully specified.
[9] Physiological and somatic anxiety are used interchangeably in the literature. Physiological anxiety is used throughout this manuscript for consistency and clarity

stable, general predisposition to experience high levels of anxiety that affects behaviour (Eysenck & Calvo, 1992) whilst state anxiety refers to a negative emotional state in response to a specific situation and is commonly associated with physiological arousal (Robinson, Vytal, Cornwell, & Grillon, 2013).

It is well-documented that anxiety affects attention allocation. The Quiet Eye (QE), defined as the final fixation on a specific location prior to the execution of a motor action, is an objective measure of visual attention, with longer QE periods leading to improved performance (Vine, Moore, & Wilson, 2011). Behan and Wilson (2008) revealed that, as anxiety increased, there was a reduction in QE duration and shooting accuracy in a simulated archery task (see Nibbeling, Oudejans, Ubink, and Daanen, 2014, for similar results). Increased variability in gaze behaviour under conditions of anxiety has been shown in table-tennis (Williams, Vickers, Rodrigues, & Hillis, 2000), aviation (Allsop and Gray, 2014) and rally driving (Wilson, Chattington, and Marple-Horvat, 2008). Attentional biases are also well-documented in anxiety-provoking situations. Participants allocate more attention to salient (Ferreira & Murray, 1983) and threatening stimuli (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & Van Ijzendoorn, 2007) because anxiety biases the attentional alerting systems (Beck & Clark, 1997). Taken together, these studies demonstrate an effect of anxiety on attention allocation.

Following a significant body of research showing an effect of anxiety on attention allocation, theoretical models that provide a mechanistic account of the relationship have been developed. Attentional bias models argue that, under anxiety, attention is biased towards threatening stimuli and individuals are unable to disengage from the processing of such information (see Weierich, Treat, & Hollingworth, 2008, for review). Self-focus theories (e.g. Explicit Monitoring Hypothesis, Beilock & Carr, 2001; Theory of Reinvestment, Masters & Maxwell, 2008) argue that, when anxious, individuals shift more attention to the skill execution process, which was previously automatic, which leads to 'overthinking' and a reduction in performance (Lewis & Linder, 1997). In contrast, distraction theories suggest that attention is diverted away from the task towards feelings of worry and apprehension in anxiety provoking situations. Such feelings utilise the attentional resource and, therefore, interfere with the efficiency of task execution contributing to a reduction in performance (Beilock & Carr, 2001).

Eysenck and Calvo (1992) proposed Processing Efficiency Theory (PET) which distinguishes between the effectiveness (i.e. the quality of performance) and efficiency (i.e. the effectiveness of performance divided by the effort) of performance. Feelings of worry are resource-intensive which leads to a reduction in the resource available for main task execution and, ultimately, a decrease in the efficiency of performance. Meanwhile, worry motivates the individual to increase their task-effort to maintain the effectiveness of performance. Eysenck and Calvo (1992) argue that anxiety effects efficiency more than effectiveness, with PET explaining that individuals experiencing higher anxiety can achieve equivalent performance by expending extra effort.

Attentional Control Theory (ACT) is a theoretical development of PET that explains how anxiety effects attentional processes, specifically (Eysenck et al., 2007). Corbetta and Shulman (2002) distinguish between two attentional control systems: a stimulus-driven bottom-up system and a goal-directed top-down system. ACT proposes that anxiety leads to an increase in bottom-up processing and a decrease in top-down processing. Therefore, more of the attentional resource is likely to be allocated to distracting stimuli (e.g. worrisome thoughts) over task-relevant stimuli. This theory also highlights compensatory mechanisms whereby individuals boost their top down control of attentional processes by increasing effort and, therefore, maintain a sufficient level of attention to successfully complete the task (Booth & Peker, 2017; Eysenck et al., 2007).

Easterbrook (1959) proposed a theory of Attentional Narrowing which describes the involuntary narrowing of the attentional window. Such narrowing leads to an increase in performance on a central task, that represents the focussing of the attentional window, and a decrease in performance on a peripheral task, due to a reduction in the range of cues that can be utilised (Easterbrook, 1959; Mueller, Smith, & Jones, 1976). Shappell and Wiegmann (2003) propose that attentional narrowing contributes to accidents in domains such as aviation due to an inability to process all peripheral information. Janelle, Singer, and Williams (1992) showed that participants in an auto racing simulation were less successful at detecting peripherally presented targets when they were anxious, but performance on the main driving task was maintained. In a dual-task study Murray and Janelle (2003) found that, as anxiety increased, search rate on a secondary task was significantly slower but performance on a central driving simulation task was maintained. Using the 7.5% CO_2 challenge model of anxiety induction, Diaper, Nutt, Munafò, White, Farmer, and Bailey (2012) reported no effect of anxiety on performance in a central tracking task but detrimental performance effects in a secondary digit response task when participants inhaled air enriched with carbon dioxide. These studies demonstrate attentional narrowing across tasks (i.e. central versus peripheral tasks) rather than to distinct objects within the same task (i.e. high versus low priority targets). The unequal attention splitting task used in Chapters 2 and 3 allows a direct test of attentional narrowing, the results of which could distinguish between fixed and flexible accounts.

Testing the theory of attention narrowing can provide insight into the structure of the attentional resource that underlies tracking. Under a fixed architectural account consisting of four slots, participants can split attention unequally between two targets in one *way.* Specifically, they can allocate one and three slots to a low and high priority target, respectively. Under conditions of anxiety, attentional narrowing would predict that participants allocate more attention to a high priority target relative to the low priority target. Since there is only one *way* to split four slots unequally, fixed accounts cannot explain results that are indicative of attentional narrowing. In contrast, flexible and hybrid slots could explain data demonstrating attentional narrowing within an unequal attention splitting MOT task.

Two types of anxiety induction have commonly been used in the literature: cognitive and physiological. Cognitive anxiety induction uses financial reward, social comparisons, performance thresholds and non-contingent feedback (e.g. participants performing in lowest 30%; e.g. Behan & Wilson, 2008; Murray & Janelle, 2003; Wilson, Vine & Wood, 2009) and aims to induce the cognitive symptoms of anxiety. It has been effectively applied in several domains including sport (e.g. Wilson, Vine, & Wood, 2009), aviation (e.g. Allsop & Gray, 2014; Allsop, Gray, Bulthoff, & Chuang, 2016) and cognitive tasks (e.g. Thompson, Webber, &, Montgomery, 2002). Physiological anxiety induction can be implemented using the 7.5% CO_2 challenge model. This model has been validated regarding its ability to induce the physiological symptoms of anxiety which, in turn, leads to the emergence of cognitive symptoms (Bailey, Argyropoulos, Kendrick, & Nutt, 2005). Two experiments examined the effect of anxiety on unequal attention splitting within a MOT framework. First, Experiment 7 used a cognitive anxiety induction technique which was unsuccessful. Therefore, Experiment 8 used the 7.5% CO_2 challenge model of anxiety induction to induce both physiological and cognitive state anxiety.

4.3 Experiment 7

Experiment 7 examined the effect of cognitively induced anxiety on unequal attention allocation in a MOT task.

4.3.1 Method

Participants. Thirty-five participants (21 females, 14 males, range 18 - 23) from the University of Bristol volunteered to take part[10]. Six participants' data were lost due to technical difficulties. G*Power version 3.1 (Faul et al., Buchner, 2007) was used to calculate sample size for all experiments. The sample size was determined using a previous study that investigated the effect of 7.5% CO_2-induced anxiety on speech perception (Mattys, Seymour, Attwood, & Munafò, 2013). This study indicated an effect size difference between gas and air of dz = 0.57. Based on this estimate, 35 participants were required to achieve 90% power to observer a similar main effect of gas at an alpha level of 5%.

[10] India Derrick assisted with data collection.

Design. A repeated measures design with two within-subject factors of anxiety (no anxiety, anxiety) and target priority (low (25%), high (75%)) was used. The order of anxiety manipulation was counterbalanced across participants and participants completed both conditions within one testing session.

Measures. The primary dependent variable was magnitude of angular error, indexed by the degree of error from the queried target's actual trajectory (i.e. the direction it was heading in) to the participant's reported trajectory at the end of the trial. The proportion of guess trials and precision of representations, calculated from the mixture modelling analysis (see Chapters 1 and 2), were also dependent variables. Blood pressure (BP), heart rate (HR), galvanic skin response (GSR) were also recorded using an OMRON M6 cuff monitor and MINDFIELD eSEnse skin responses, respectively. There were also two questionnaires: 1) The Spielberger State (SSAI-State) (Spielberger et al., 1983); 2) Positive and Negative Affect Schedule (PANAS) (Watson, Clark, & Tellegen, 1988).

Stimuli. The trajectory-tracking task was used. Participants completed 5 practice trials followed by 120 experimental trials in 2 blocks (i.e. anxiety, no anxiety conditions). The experiment lasted approximately 1 hour.

Procedure. Prior to the study session, participants received the information sheet and details of their study session via email. On arrival, participants were given the opportunity to ask any further questions. They then completed the two baseline questionnaires and baseline HR and BP measures were recorded. Participants completed five practice trials to familiarise themselves with the task. Next, a device was fitted to participant's left hand to record the galvanic skin response (GSR) throughout each anxiety condition. Participants were not aware of the anxiety manipulation and, therefore, were told that the GSR was used to measure their engagement with the task. HR and BP was recorded after the completion of each condition.

Participants were then given instructions related to the condition in which they were about to perform (i.e. no anxiety, anxiety). The order of instructions and, therefore, conditions, was counterbalanced across participants. After having received their first set of instructions, participants completed the questionnaires and then began the experimental task. At the end of the task, participants were given the other set of instructions, filled out the questionnaires and completed the experimental task again. After having completed both conditions, the participants received a full debrief.

Task Instructions

No anxiety condition. Participants were told that an experiment was being piloted to check the visual displays, therefore, generating a relaxed environment. Participants received non-evaluative instructions asking them to simply have a go at the task and do their best.

Anxiety condition. State anxiety was induced using techniques adapted from the sporting literature (e.g. Wilson, Vine, & Wood, 2009). Participants were told that they must perform above an 80% correct threshold in order for their data to be used in the study and that their results would be published around the department. Participants were also told that the top three performing participants would receive a monetary reward. During testing the experimenter walked up and down behind them and reminded them of their need to be above 80%, by commenting during breaks.

4.3.2 Results and Discussion

To assess whether the anxiety manipulation had been successful, reactivity scores were calculated by subtracting the baseline recordings from each measure. Paired-samples t-tests were then conducted. Participants heart rate reactivity was higher in the anxiety (M = 5.3, SD = 9.15) compared with the non-anxiety condition (M = 1.5, SD = 10.23), $t(28) = 3.57$, $p = .001$, $d = 2.09$. There was, however, no effect of anxiety condition on blood pressure (both SBP and DBP: $t < 1.88$, $p > .070$) or galvanic skin response $t(20) = 0.17$, $p = .868$, $d < 0.01$. Results from the questionnaires also revealed no difference in subjective anxiety (all $t < 0.38$, $p > .706$). Taken together, there is limited evidence that the anxiety manipulation was successful.

LME analysis was used. Anxiety and Target Priority were entered into the model as fixed effects, along with an Anxiety by Target Priority interaction. There was also a random intercept for subjects. There was a main effect of target priority ($t = 3.81$, $p = .005$), with a lower magnitude of angular error for the high priority targets (see Figure 4.1, left panel). There was neither a main effect of anxiety ($t = 0.48$, $p = .633$), nor an interaction ($t = 0.81$, $p = .419$). There was a main effect of target priority on the proportion of guessing ($t = 2.13$, $p = .035$), with a lower proportion of guessing for the high priority targets (see Figure 4.1, right panel). There was neither a main effect of anxiety ($t = 0.32$ $p = .752$), nor an interaction ($t = 0.67$, $p = 501$). There was no effect of target priority or anxiety on the precision of tracking and no interaction (all $t < 1.05$, $p > .296$). A possible explanation for this is that six participants data was lost and, therefore, there was not sufficient power to detect an effect of priority on precision of tracking. Post-hoc analysis indicated an effect size *dz* = 0.12 for comparison between low and high priority targets on precision of tracking which achieved only a 16% chance of detecting the effect.

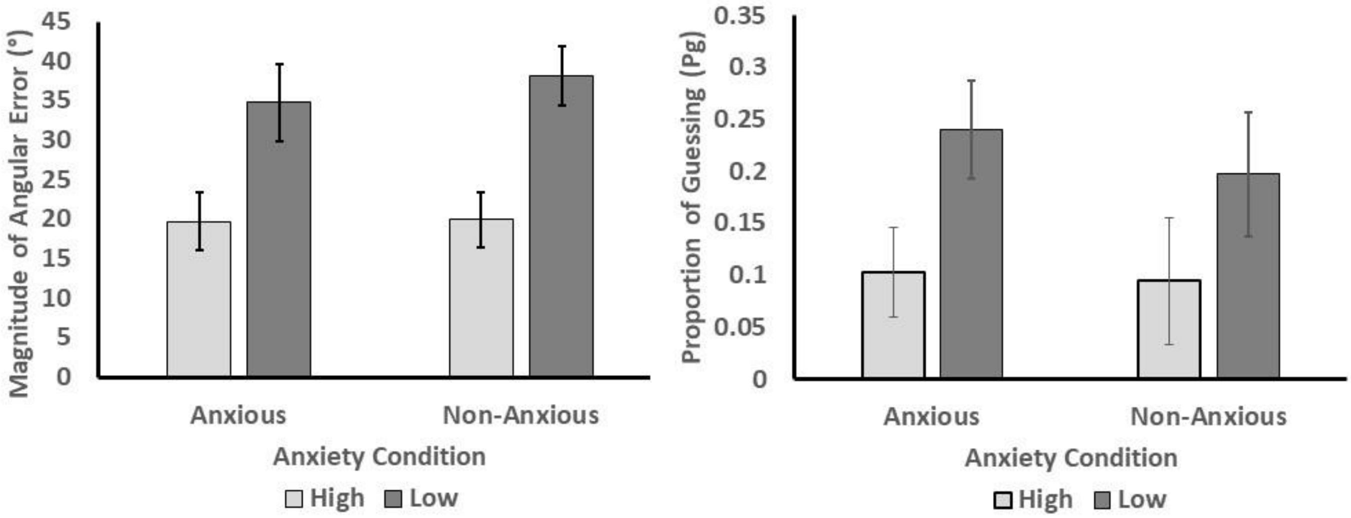


Figure 4.1. Mean magnitude of error (left panel) and proportion of guessing (right panel) for each condition in Experiment 7. Error bars represent 95% within-subject confidence intervals using Morey (2008).

Taken together, these results suggest that the anxiety manipulation was not successful. Although there was evidence for higher heart rate in the anxiety condition, it is likely that this reflects an increase in task engagement because participants were given a performance threshold (Seery, 2011) rather than participants experiencing anxiety. Although this cognitive anxiety induction method has frequently been used (e.g. Behan & Wilson, 2008; Murray & Janelle, 2003; Wilson, Vine & Wood, 2009), it has most commonly been in the sporting domain (although it has also been used in cognitive tasks, albeit less frequently). In such tasks, the participants often have an interest in the sporting task and are competing against their team mates which likely increases motivation and leads to successfully anxiety inductions. In contrast, the MOT task used here was not of high importance or relevance to the participant's interests and, therefore, participants may not have been sufficiently motivated to experience anxiety.

Psychological paradigms can misrepresent anxiety as a predominantly cognitive response, but anxiety results in both physiological and cognitive symptoms (Bailey, Kendrick, Diaper, Potokar, & Nutt, 2007; Seddon et al., 2011). An alternative method of anxiety induction is the 7.5% CO_2 challenge model of anxiety induction which induces both the physiological and cognitive symptoms of anxiety (Bailey et al., 2005, although see Hopko, McNeil, Lejuez, Ashcraft, Eifert, & Riel, 2003, for discussion on the extent to which cognitive arousal (e.g. worry) is induced). The inhalation of CO_2 leads to hypercapnia (increased levels of CO_2 in the body) which changes the pH level of the blood, resulting in increased respiration as a compensatory response. This leads to secondary physiological changes such as increased heart rate (HR) and systolic blood pressure (SBP). Cognitive appraisal of the physiological effects leads to the psychological symptoms of anxiety, evidenced by increases in self-reported anxiety, fear and tension, and decreases in relaxation (Bailey & Nutt, 2008; Cooper et al., 2011; Diaper et al., 2012).

Research has used the 7.5% CO_2 challenge model of anxiety induction to explore the effect of anxiety on numerous cognitive domains (see Fluharty, Attwood, & Munafo, 2016, for a review). Easey et al. (2018) showed that state anxiety negatively affected simple information processing and Attwood, Catling, Kwong, and Munafo (2015) showed anxiety contributed to a decrease in accuracy for face memory. Specifically relevant to attention allocation, Garner, Attwood, Baldwin, James, and Munafò (2011) showed that, in an emotional antisaccade task, anxious participants incorrectly directed attention, indexed by eye movements, towards threating stimuli on antisaccade trials. Given its extensive use with cognitive tasks, this method of anxiety might better induce anxiety within a MOT framework.

4.4 Experiment 8

Since Experiment 7 was unsuccessful at inducing anxiety in participants, Experiment 8 used the 7.5% CO_2 challenge model of anxiety induction which has been validated as inducing both the physiological (e.g. increase in systolic blood pressure and heart rate) and psychological (e.g. increased ratings of anxiety and fear) effects of anxiety (Bailey et al., 2005).

4.4.1 Method

Participants. Thirty-six participants (19 females, 17 males, range 18 - 27) took part. One participant's data was lost due to technical issues. Participants were recruited from existing mailing lists, the School of Psychological Science website, posters and word of mouth (see Appendix 3 for Consolidation Standards of Reporting Trials (CONSORT) Flow Diagram)[11]. The sample size calculation was identical to Experiment 8. After an expression of interest, participants had a 10 minute telephone screening to asses study eligibility. Having completed the telephone screening, participants were invited to attend a day screen and underwent further tests to ensure they met the eligibility criteria (see Appendix 2). All participants were reimbursed £20 for their time. A total of 55 participants attended day

[11] Hannah Cook, Megan Manuel and Grace Lakey assisted with data collection.

screening, with 7 failing to meet at least one eligibility criteria and 12 withdrawing during the CO_2 inhalation phase of the study (see Appendix 2).

Design. A repeated measures design with two within-subject factors of gas (medical air, CO_2) and target priority (low, high) was used. The order of gas inhalation was counterbalanced across participants using a random number generator (http://www.randomizer.org). Administration of the gas was single-blind for safety measures.

Materials

Gas mixture. The gas mixtures used were CO_2 7.5%/O2 21%/N 71.5% and medical air (O2 21%). The gases were administered through an oro-nasal facemask (Hans Rudolph, Inc., Shawnee, KS) which was attached to a 500 L Douglas bag (Cranlea Human Performance Testing Ltd., Birmingham, UK) with tubing. To confirm the validity of the 7.5% CO_2 model as an anxiety manipulation paradigm, subjective responses (STAI-S) and physiological measures (HR and BP) were recorded after each inhalation.

Multiple-Object Tracking Task. The MOT task was identical to the one used in Experiment 7. Participants first completed five practice trials. They then completed 120 experimental trials split into two blocks (i.e. gas, CO_2). Each block lasted approximately 12 minutes.

Measures

Cardiovascular Measures. Blood pressure and heart rate was recorded using the OMRON M6 cuff.

Tracking accuracy. Magnitude of angular error, proportion of guessing and precision of tracking were estimated to obtain indexes of tracking accuracy in line with Experiment 7.

Questionnaires. Questionnaire measures included: 1) the Spielberg State (SSAI) and 2) Trait Anxiety Inventory (STAI) Spielberger et al., (1983); 3) the Anxiety Sensitivity Index (ASI; Peterson & Reiss, 1992); 4) the Positive and Negative Affect Schedule (PANAS; Watson, Clark & Tellegen,1988); 5) the Eysenck Personality Questionnaire-Revised (EPQ-R; Eysenck & Eysenck, 1991)[12]. Psychiatric history was assessed using the Mini International Neuropsychiatric Interview (Sheehan et al., 1998).

Procedure

Prior to the session, participants underwent a telephone screen to assess basic eligibility. Eligible participants attended a single test session, at which they were given the opportunity to read the study information sheet again and ask any questions. Further screening assessments were conducted to confirm the self-reported information from the telephone screening and identify any changes (e.g. new medication) since the telephone screening. If eligibility was met, baseline questionnaire (SSAI, STAI, PANAS, ASI) and cardiovascular (blood pressure [BP] and heart rate [HR]) measures were recorded. Participants were then given instructions about the MOT task and completed five practice trials to familiarise themselves with the procedure. Once participants were happy to continue, the first inhalation stage began. Participants were given information about the inhalation and informed they were allowed to stop at any point if they wished to do so. The oro-nasal mask was then fitted,

[12] STAI, ASI and EPQ were included to support a wider research question and are therefore not explored in this chapter.

ensuring maximum comfort. The inhalation began with 60s of free breathing before the tasks were started (this allowed for the gas to start taking effect before data collection began). Inhalations then continued for approximately 12 minutes whilst participants completed the 60 trials of the MOT task. Immediately after each inhalation, measures of BP, HR, SSAI, and PANAS were completed. Participants were asked to think back to, and answer, on the basis of when the gas was at its strongest. There was a 30-min washout period between inhalations. The second inhalation followed the same procedure as the first. After the inhalations were complete, participants remained in the room for a minimum of 20 minutes, to allow any effects to dissipate and ensure good recovery from inhalation. Before participants were able to leave, BP and HR were measured to establish that they had returned to baseline. The testing session lasted approximately 2.5 hours. Participants were then debriefed and reimbursed. A follow-up call was conducted within 24 hours to assess whether any adverse events had occurred.

4.4.2 Results and Discussion

Reactivity scores were calculated to check the anxiety manipulation was successful. One and two participants were removed from the PANAS and SSAI analysis, respectively, due to incomplete data. Baseline recordings were subtracted from measures after each inhalation and paired-samples *t-tests* were then conducted. State anxiety (SSAI), negative affect (PANAS-negative), HR and SBP increased and positive affect (PANAS-positive) decreased more from baseline after the CO_2 inhalation compared with air inhalation, confirming the validity of the anxiety manipulation.

	Mean (SD)		df	*t-value*	*p-value*	Effect Size
	Gas	CO2				(*dz)*
SSAI	3.29 (7.57)	17.35 (11.68)	33	8.51	<.001	1.37
PANAS-negative	1.00 (4.41)	6.11 (6.49)	34	5.10	<.001	0.89
PANAS-positive	-2.80 (6.62)	-8.09 (7.32)	34	5.06	<.001	0.71
SBP (Reactivity)	0.17 (9.63)	6.83 (15.38)	35	2.48	.018	0.49
DBP (Reactivity)	1.81 (6.04)	3.11 (7.15)	35	0.88	.383	0.20
HR (Reactivity)	-3.31 (6.89)	1.00 (8.33)	35	2.99	.005	0.56

Table 1. Descriptive and inferential statistics for manipulation checks in Experiment 8.

The LME analysis conducted was identical to Experiment 7**.** There was a main effect of target priority on the magnitude of angular error (t = 2.82, p = .006), with a lower magnitude of angular error for the high priority targets compared to the low priority targets (see Figure 4.2, left panel). There was neither a main effect of anxiety (t = 0.26, p = .796), nor an interaction (t = 0.25, p = .804). There was a main effect of target priority on the proportion of guessing (t = 2.35, p = .020), with a less guessing for the high priority targets (see Figure 4.2, right panel). There was neither a main effect of anxiety (t = 0.36 p = .722), nor an interaction (t = 0.53, p = .595). There was no effect of target priority or anxiety on the precision of tracking and no interaction (all t < 1.65, p > .101).

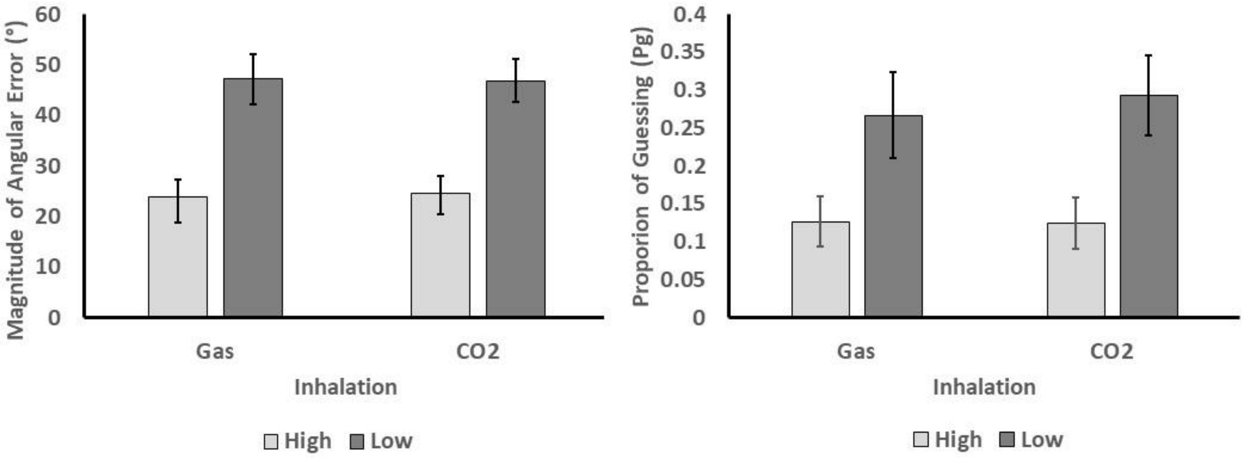


Figure 4.2. Mean magnitude of error (left panel) and proportion of guessing (right panel) for each condition in Experiment 8. Error bars represent 95% within-subject confidence intervals using Morey (2008).

The results show that the 7.5% CO_2 challenge model of anxiety induction was successful in inducing state anxiety, highlighting its advantages over cognitive anxiety induction. There was no evidence for an effect of anxiety on attention allocation, indexed by magnitude of angular error, proportion of guessing and precision of tracking. There was an effect of target priority on both the magnitude of angular error and proportion of guessing, with higher tracking accuracy and a lower proportion of guessing observed for high priority targets. This finding fits with results from Chapters 1 and 2 indicating that participants can split attention unequally, although there was no effect of priority on precision. There was also no evidence for an interaction and, therefore, no evidence for attentional narrowing.

Eysenck and Calvo (1992) highlighted the complexity and inconsistency in findings regarding the direction of the effect of anxiety on performance. There is evidence demonstrating that both an increase and decrease in performance is possible under anxiety-provoking situations (see Wilson, 2012, for a review). These differential responses are well-captured in the sporting literature which distinguishes between *choking* (i.e. suboptimal performance, Hill, Hanton, Matthew, & Fleming, 2010) and *clutch* (i.e. superior performance in anxiety-provoking situations, Otten, 2009) performance. An exploratory investigation of the data was therefore conducted to examine whether the null effect of anxiety on tracking accuracy was due to the sample consisting of some *chokers* and some *clutch* performers. To split the sample, difference scores were calculate by subtracting the magnitude of error during the inhalation of gas (collapsed over target priority) from the magnitude of error during the inhalation of CO_2 (also collapsed over target priority). Ordered in terms of change in magnitude of angular error, Figure 4.3 (left panel) showed that some participants demonstrated a decrease in magnitude of error from the gas to CO_2 condition (i.e. negative value) and others demonstrated an increase (i.e. positive value) indicative of individual differences. Figure 4.3 (right panel) shows the distribution of the data and further suggests that the possibility of sub-groups should be explored in future research.

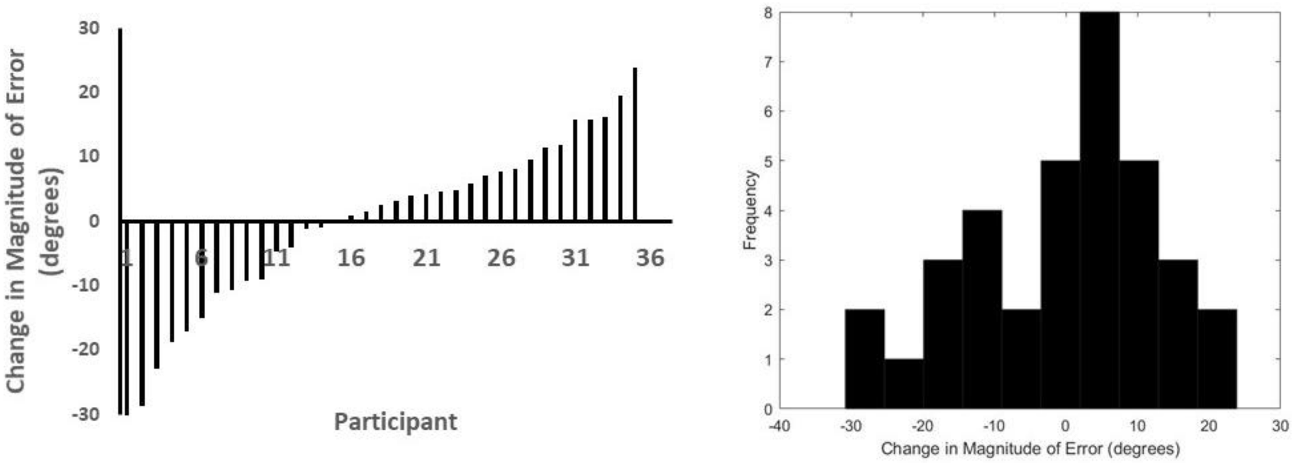


Figure 4.3. Change in magnitude of error between the air and CO_2 inhalation for each participant (left panel) and the distribution of change scores (right panel).

4.5 General Discussion

Two experiments investigated the effect of state anxiety on unequal attention allocation in a MOT task to test the theory of attentional narrowing. Experiment 7 used a cognitive anxiety induction technique, but this method was not successful at inducing anxiety. Experiment 8 therefore used the 7.5% CO_2 challenge model of anxiety induction. Although the anxiety manipulation was successful, there was no evidence for attentional narrowing. Therefore, these results cannot further distinguish between fixed and flexible accounts of MOT beyond the findings from Chapters 2 and 3.

In line with Chapters 2 and 3, both experiments revealed evidence for an effect of target priority on tracking accuracy (i.e. magnitude of error, proportion of guessing), indicating unequal attention allocation. Nevertheless, there was no effect of priority on the precision of tracking which contrasts the results from Chapters 2 and 3. This indicates that the higher proportion of guessing trials for the low priority target drives the differences revealed in the magnitude of error index between high and low priority targets. A possible explanation is that the fewer experimental trials in this experiment (i.e. 60 trials compared to 120 and 250 trials in previous experiments), which was required to fit the experimental task into the 12 minutes of CO_2 inhalation for safety reasons, masked the effects of priority on precision.

Experiment 8 also revealed no evidence for an effect of anxiety on tracking performance. An exploratory investigation into the data indicated that it is possible that any effect of anxiety was masked because there were two types of participants: those whose performance increased and those who decreased during the CO_2 inhalation. Importantly, the order of inhalations was not responsible for the different directions of performance indicated. Specifically, participants did not *always* perform better in the inhalation that they completed second which would indicate training effects rather than individual differences effects. This is, perhaps, unsurprising given previous studies showing that the effect of anxiety can be bi-directional (e.g. Hill et al., 2010, Otten, 2009) and several theories which recognise individual differences in response to anxiety.

Some theories suggest an individuals' appraisal of an anxiety-provoking situation affects performance (e.g. Jones & Swain, 1992; Lazarus & Folkman, 1984). The Directional Perspective argues that an individual interprets the symptoms of anxiety as either debilitative (i.e. distract or interfere with task execution) which leads to bad performance, or facilitative (i.e. help mental preparation) which leads to good performance (Jones & Swain, 1992). This theory links to the Transactional Perspective of Stress (Lazarus & Folkman, 1984) which suggest that individuals evaluate the demands and resources available to them when completing a given task. Poor performance is observed when perceived demands exceed available resources, whereas good performance is seen when resources outweigh demands. Although these models explain the mixed results regarding the effect of anxiety on performance, they are entirely descriptive and do not explain the underlying mechanisms driving this relationship. Further research is required to better understand individual differences in response to anxiety and develop methods to capture such disparities in experimental designs.

Some participants showed no effect of anxiety on MOT performance. A possible explanation for a genuine null effect of anxiety on tracking accuracy is compensatory effort by participants during the inhalation of 7.5% CO_2, an idea proposed by Attentional Control Theory (Eysenck et al., 2007). Hardy and Hutchinson (2007) showed that an increase in the cognitive appraisal of anxiety (which was demonstrated in Experiment 8) leads to an increase in effort. In line with Attentional Control Theory, participants may have adopted compensatory strategies such as utilising additional processing resources when they experienced symptoms of anxiety which contributed to equivalent performance in the air and CO_2 condition (Derakshan & Eysenck, 2009). This interpretation fits with Diaper et al. (2012), who found an effect of CO_2 inhalation on physiological measures and subjective ratings of anxiety but not on performance. The authors suggested that this was due to participants exerting greater cognitive effort, although note these authors did not look for individual differences. Since Experiments 7 and 8 were not designed to test ACT, indexes of effort were not recorded. Future research could directly address this by using pupillometry measures to index effort (Alnæs, Sneve, Espeseth, Endestad, van de Pavert, Laeng, 2014). Alternatively, Diaper et al., (2012) showed that reaction time can be used to index effort, and subjective questionnaires (e.g. Subjective Rating of Mental Effort, Paas, 1992) have also been validated in quantifying mental effort (e.g. Young, Van Merrienboer, Durning, & Ten Cate, 2014). Together, these methods could provide insight into the extent to which effort contributes to the maintenance of performance under pressure.

Hopko et al., (2013) suggested that the 7.5% CO_2 challenge manipulates physiological arousal, but does not effect all hallmarks of cognitive anxiety. Endler and Kocovski (2001) argue that there are at least two facets of state anxiety: cognitive worry and autonomicemotional. The automatic-emotional feelings (e.g. “I am tense” from the SSAI) are directly affected by physiological arousal whereas the cognitive worry feelings (e.g. “I am worried” from the SSAI) might not be. A participant in this experimental set up knows that they are about to inhale air enriched with CO_2 and also knows they are in a safe place and can therefore rationalise the physiological effects and not feel worried. Therefore, although the subjective questionnaires indicate an increase in cognitive anxiety in the CO_2 compared to air inhalation, such changes could be driven by the physiological components of anxiety only rather than an overall increase in all hallmarks of anxiety. Therefore, it is possible that cognitive anxiety remained relatively low and the physiological arousal induced by the CO_2 inhalation may not have reached a threshold at which detrimental effects on attentional performance were observed.

The participant sample and dropout rate from Experiment 9 requires consideration. Twelve participants (24%) withdrew during the inhalation of CO_2. This high rate of withdrawal has not been reported in other research using this anxiety induction technique (e.g. Bailey et al., 2005; Diaper et al., 2012), although not all studies report any rate of withdrawal and, therefore, this may be a reporting omission. This withdrawal rate is, however, high compared to other work from this lab, although withdrawal rates have increased over time. Therefore, this study is important in highlighting the potential bias in the remaining sample as driving the results. Spielberger (1966) showed that trait anxious individuals are more prone to experiencing state anxiety. Therefore, it is possible that the participants who withdrew were high trait anxious, which resulted in them experiencing a heightened response to inhaling CO_2 and, ultimately, their withdrawal. Therefore, the remaining sample could have represented participants who did not respond as strongly and were less likely to show any effects. Due to ethical guidelines, we were unable to analyse the demographics (e.g. trait levels of anxiety) of those participants who withdrew. Nevertheless, Fluharty, Attwood, and Munafò (2016) showed an association between trait anxiety and participants' response to the CO_2 inhalation, with high trait anxious individuals being more likely to respond (i.e. experience anxiety) to both CO_2 and air and, ultimately perform similarly in both conditions. Future research should consider individual differences in response to anxiety during recruitment and analysis.

This chapter tested the theory of attentional narrowing to gain insight into the structure of the resource that underlies MOT. There was no interaction between anxiety and priority and, therefore, no evidence for attentional narrowing. Further research is needed to examine the extent to which individual differences effect anxiety research and assess the efficacy of the 7.5% CO_2 challenge model of anxiety induction at inducing all hallmarks of cognitive anxiety.

Chapter 5 Discussion

5.1 Chapter Summary

There is continued debate regarding the nature of the attentional resource that underlies tracking. Further empirical work is therefore needed to distinguish between fixed and flexible accounts of attention. Current theories of MOT are based on the results of experiments using equal attention splitting paradigms. Since this is atypical of the real world in which an individual often needs to prioritise one object relative to another, this thesis introduced a novel unequal attention splitting paradigm to distinguish theories of MOT. In this chapter, the primary findings from the three empirical chapters are summarised. Theoretical and practical implications of this work are discussed and directions for future research are identified. Finally, the main conclusions of this thesis are outlined.

5.2 Overview of Main Findings

5.2.1 Chapter 2: Goal-directed attention allocation during multiple object tracking

In everyday situations, it is common that individuals must prioritise one object relative to another and so allocate attention unequally. Chapter 2 investigated whether participants can split attention unequally between moving objects. Four experiments revealed evidence for unequal attention splitting in a goal-directed manner in standard MOT, position- and trajectory- tracking tasks. Participants could allocate more attention to a high priority target, indexed by a lower magnitude of error, lower proportion of guessing and higher precision. Experiments 1 and 2 investigated the extent to which this ability was fine-grained, namely the precision with which attention can be split. There was inconclusive evidence for fine-grained splitting. It is possible that participants have the capacity to split according to any unit but were unable to gauge what a given unit of the attentional resource was or were not sufficiently motivated to split beyond a binary *more* and *less* mechanism. To overcome these limitations, an alternative method of manipulating attention in a goal-directed manner, such as reward, was required.

Since guessing rates remained low across all conditions and tracking demands were below capacity in all experiments, it is unlikely that participants performed single object tracking. However, it is possible that, on some trials, participants dropped a target leading to the complete withdrawal of attention from that target and, therefore, single object tracking for part of a trial. To explore *how* unequal attention splitting is achieved, research must address the within-trial behaviour of participants. One possible method is to explore the relationship in tracking accuracy between targets presented simultaneously on a given trial.

5.2.2 Chapter 3: Reward-based unequal attention allocation in position tracking

Since it is possible that participants lacked motivation when completing the Experiments in Chapter 2, Chapter 3 investigated reward-based unequal attention allocation. Chapter 3 also aimed to explore the relationship in tracking accuracy between two targets on a given trial to further understanding *how* unequal attention splitting is supported. Experiment 4 revealed unequal attention splitting in a reward-based manner supporting research from working memory also showing unequal splitting in response to reward (Morey et al., 2011).

Experiments 5 and 6 introduced a double-probe procedure in which an index of tracking accuracy was obtained for both targets to obtain a TAC score. There was no effect of splitting condition on TAC scores in either experiment. Exploratory analysis revealed poorer tracking accuracy for the second response compared with the first response, which could have masked any effect of splitting type on TAC scores. This fits with other research documenting the speed at which memory for target locations degrade (e.g. Howard & Holcombe, 2008; Tripathy & Barrett, 2004) and requires further consideration. Understanding how other cognitive mechanisms (e.g. memory) or internal factors (e.g. anxiety) interact with MOT can provide insight into the complex interplay of processes and the structure of the attentional resource.

5.2.3 Chapter 4: No evidence for attentional narrowing within a MOT framework

Chapter 4 tested the theory of attentional narrowing using the unequal attention splitting MOT task from Chapters 2 and 3. Experiment 7 used a cognitive anxiety induction technique which was unsuccessful. Experiment 8 therefore used a physiological anxiety induction technique which was deemed successful at inducing state anxiety. There was no evidence for attentional narrowing and, therefore, limited further theoretical insight beyond Chapters 2 and 3. In line with Chapters 2 and 3, there was evidence for unequal attention splitting between two moving targets in both experiments (although contrary to Chapters 2 and 3, there was no effect of target priority on precision). There was no effect of anxiety on MOT performance. This could be due to individual differences in the sample, with some participants responding positively and others negatively to the anxiety induction resulting in a null effect. Alternatively, participants could have exerted more effect during the inhalation of CO_2 which acted as a compensatory mechanism to achieve an equivalent level of performance. The method of anxiety induction requires further consideration to the extent to which certain characteristics of state anxiety (e.g. worry, apprehension) are induced by the technique.

5.3 Theoretical Implications

Eight studies revealed evidence for unequal attention allocation in a MOT task demonstrating some flexibility to the attentional resource. These results cannot be accounted for pure fixed models (i.e. four or five slots support tracking). Fixed models could account for such findings with the additional assumption that more than one slot could be allocated to a given target (e.g. 3 and 1 slot(s) on a high and low priority target, respectively) but this explanation is captured by hybrid models of attention allocation. Specifically, Zhang and Luck's (2008) *slots + averaging* model suggests that when the number of items to be tracked (i.e. when applied to MOT) is below capacity, each item can be assigned more than one slot. Since there were only two targets, tracking load was below capacity and, therefore, it is possible that participants allocated one and three slots to a low and high priority target, respectively, to achieve unequal attention splitting. A *slots + resources* account could also explain this pattern of results, with participants allocating one slot to each target but distributing more of the resource to the high priority targets.

Chapter 3 showed that there was no correlation in tracking accuracy between two targets presented simultaneously. This is evidence against single object tracking, which would predict a strong negative correlation (i.e. an increase in tracking accuracy for the tracked target accompanied by a decrease in tracking accuracy for the untracked target).

This result also provides insight into the extent to which tracking is achieved by a serial or parallel mechanism (or a combination of both), which is another debate within the MOT literature. Serial accounts suggest that participants attend to only one target at a given time and rapidly switch their attention between all targets (e.g. d'Avossa et al., 2006; Oksama & Hyona, 2008). Therefore, a serial account would predict a negative correlation in tracking accuracy between two targets because the entire attentional resource will be allocated to one target and, therefore, withdrawn entirely from the other. Parallel accounts suggest that attention is distributed across all targets simultaneously (e.g. Alvarez & Franconeri, 2007; Kazanovich & Borisyuk, 2002; Howe et al., 2010). Such accounts would predict a positive correlation in tracking accuracy because any variability in performance, such as attentional fluctuations across trials, would be consistent across both targets. Since there was no evidence for a correlation in Chapter 3, this is more consistent with contributions from both switching and sharing of processing resources between targets for tracking. For example, the task demands might determine the extent to which a serial or parallel mechanism supports tracking with more serial switching on trials when there is less of the attentional resource available (Howard & Holcombe, 2008).

5.4 Practical Implications

The modified MOT task more closely reflects unequal attention allocation captured in real-world tracking and, therefore, has practical implications. Chapters 2, 3, and 4 revealed evidence for unequal attention splitting. This ability could improve performance in safety critical occupations such as the military, or activities such as team sports. For example, in the military a soldier would likely need to allocate more attention to the enemy to avoid being shot but also maintain awareness of their own personnel to avoid any accidents. Meanwhile in team sports, a footballer would likely pay more attention to the approaching attackers but still direct some attention to the location of their team mates. A large body of research has examined the efficacy of cognitive training to improve performance in several domains including the military (Blacker, Hamilton, Roush, Pettijohn, & Biggs, 2018) and sport (Appelbaum & Erickson, 2018). Of high relevance to tracking is the development of Neurotracker ™, a 3D-MOT (with a 2D screen) task proposed to optimise mental abilities when processing dynamic scenes (Faubert & Sidebottom, 2012) that has been shown to improve WM in the military (Vartanian, Coady, & Blackler, 2016) and decision-making in football (Romeas, Guldner, & Faubert, 2016). Further developments of cognitive training tasks to incorporate unequal attention splitting could be advantageous for performance in occupations requiring tracking.

Chapter 3 demonstrated a decrease in accuracy for target positions as the time to localise them increased, highlighting a rapid decline in memory (through either interference or decay). This has practical implications given that, in the real-world, we must track multiple moving objects around our whole visual environment, rather than within one location (i.e. a computer screen). For example, a CCTV operator must monitor numerous screens, each of which contains multiple moving objects. If every time they shift their attention to a different screen, their representations of the objects in the previous screen degrade, this could contribute to errors. Given the growing evidence highlighting the rapid decline in memory within a MOT framework (e.g. Howard & Holcombe, 2008; Tripathy & Barrett, 2004), more research understanding the rate of memory decay within a MOT framework is warranted.

5.5 Future Directions and Limitations

Three empirical chapters reveal behavioural evidence that participants can split attention unequally. A limitation of behavioural methods is that no conclusions can be drawn about the online changes in the spatial distribution of attention. As demonstrated in the visual search literature, behavioural and electrophysiological evidence can generate conflicting findings (e.g. Woodman & Luck, 1999; 2003) and, therefore, electrophysiological methods should be used with the unequal attention splitting paradigm. Drew, Horowitz, and Vogel (2013) used Contralateral Delay Activity (CDA) amplitude to index the number of items being tracked within a given trial and how this was mediated by target speed and number of distractors. This enabled a distinction between trials on which swapping and dropping occurred. The behavioural experiments presented here cannot distinguish between these events, which have implications for the conclusions drawn regarding unequal attention splitting, further reinforcing the need to adopt ERP indexes of attention.

Chapter 3 aimed to investigate the relationship in tracking accuracy between two targets presented simultaneously. The TAC score did not differentiate between equal and unequal splitting trials because of the poor tracking accuracy for the second response. Despite the implications of this result for memory, this study provided limited insight into the relationship in tracking accuracy. Double-report procedures have the potential to demonstrate behavioural differences in equal compared with unequal attention splitting but this procedure needs refining. It is possible that the motor action required to press the screen to record the first response resulted in a drift of the finger that would be used to record the second response and, therefore, imprecision in one's response. Moreover, using a stylus rather than a finger would facilitate a more precise response.

Despite significant evidence for unequal attention splitting, no strong conclusions can be drawn regarding the extent to which this ability is fine-grained. Existing fixed models of tracking must add additional assumptions (e.g. more than one slot can be allocated to a single object) to explain the results presented here but, currently, the results cannot distinguish between fixed and flexible accounts. To achieve this, more targets need to be introduced to the task to examine the accuracy-priority slope. Flexible accounts would predict a gradual increase in accuracy as priority increases because any type of attention splitting is possible (e.g. 31% vs 23% vs 46% over three targets). In contrast, fixed accounts would predict a more stepped increase because there are only a limited number of ways in which slots can be split. Specifically, there is only one *way* in which 4 or 5 slots could be split unequally between three targets. Targets 1, 2 and 3 could be allocated 1, 2, and 3 slots, respectively. Therefore, different types of attention splitting according to either priority or reward would lead to the same results. Results indicative of fine-grained splitting could be taken as strong evidence against fixed models of MOT.

Experiment 8 revealed no evidence for an effect of anxiety on MOT performance. It is possible that the null effect is due to individual differences in participants' response to anxiety. Specifically, the participant sample may have consisted of both *clutch* (i.e. positive response to anxiety) and *choke* (i.e. negative response to anxiety) performers which resulted in no effect of anxiety across the entire participant sample. Given the mixed results reported in the literature that highlight individual differences in participants response to anxiety (Eysenck and Calvo, 1992; Wilson, 2012), future research must address this factor during recruitment and analysis. In cognitive psychology, median splits have commonly been used combine a continuous variable into categorical variables during data analyses which is a possible avenue for capturing individual differences (De Coster, Gallucci, & Iselin, 2011; Iacobucci, Posava, Kardes, Schneider, & Popvich, 2015).

Multiple object tracking (MOT) research is commonly justified as providing insight into the attentional mechanisms underlying everyday skills (e.g. driving) and occupations (e.g. CCTV monitoring). An aim of this thesis was therefore to modify the MOT task to reflect real-world tracking more closely. Further such developments of the MOT task are still required to directly test competing models of tracking. Standard MOT tasks index tracking accuracy by requiring participants to judge the status (target or non-target), direction, or location of objects at the end of a trial. This is atypical of the real world in which individuals must both track and monitor their environment to allow them to respond to certain events that could occur. For example, a driver must slow down when they see the brake lights on the car in front come on. Existing response procedures capture participants’ knowledge about the current characteristics of an object. They do not, however, provide any insight into how long it takes participants to detect a change in an object’s properties (e.g. trajectory, features). This ability is a crucial feature of real-world tracking where individuals must split attention across multiple spatially distinct objects until a certain event happens that requires an action, for example air traffic controllers monitoring for conflicting routes of aircraft (Remington, Johnston, Ruthruff, Gold, & Romera, 2000). Therefore, understanding the capacity and time limits for monitoring moving objects for the detection of, and reaction to, critical events is required.

Some researchers have examined participant's ability to monitor for changes within a MOT task (e.g. Bahrami, 2003; Sears & Pylyshyn, 2000; Vater, Kredel, & Hossner, 2016) but none of these studies investigate the basic effect of set size on reaction time to detect target-changes which could help inform the debate regarding the structure of the attentional resource. Flexible accounts of MOT would predict a graded decline in reaction time as set size increases (i.e. slower) because when fewer items are tracked, the resolution of tracking is higher (e.g. Alvarez & Franconeri, 2007). Fixed theories would predict no effect of set size because each target would be assigned a pre-attentive pointer to support tracking. Importantly, fixed theories do not suggest that pointers track featural or identity information regarding an object (Pylyshyn, 1989) but this highlights that they are an incomplete model of MOT. Scholl, Pylyshyn, and Franconeri (2001) distinguished between three types of visual property available during tracking. Individuality allows participants to distinguish one object from another. Spatiotemporal properties refer to an object's location, direction, motion and trajectory information which are updated when that object moves. Featural properties describe an object's appearance, including colour, shape, lightness and texture and can change during a tracking. Whilst there are theories that directly address how spatiotemporal (e.g. Pylyhsyn, 1989; Alvarez & Franconeri, 2007) and individuality (e.g. Oksama & Hyönä, 2004) properties are tracked, no models describe the mechanism that supports the tracking of featural properties. A complete model of tracking should be able to explain how all three properties are tracked.

Other developments can also provide insight into the reference frames that support tracking. All chapters presented the MOT task on a single computer screen which is atypical of the real world in which individuals distribute attention to targets in different locations within the visual environment (i.e. not just within a single computer screen). Research has shown that viewpoint changes can affect tracking (Huff, Meyerhoff, Papenmeier, & Jahn, 2010; Huff, Papenmeier, Jahn, & Hesse, 2010), with eye-tracking research suggesting that gaze on the centroid becomes more stable during viewpoint changes (Huff, Papenmeier, Jahn, & Hesse, 2010). Further investigation into the effect of changes in viewpoint can provide insight into the extent to which scene-based and object-based reference frames are utilised during tracking.

Although there was no evidence for an effect of anxiety on MOT performance, understanding the interplay between internal factors (e.g. fatigue) and attention allocation is required. Research has shown that fatigue effects attention allocation, with mental fatigue proposed to contribute to both inefficient processing (Hopstaken, van der Linden, Bakker, & Kompier, 2016) and task disengagement (Hopstaken, van der Linden, Bakker, & Kompier, 2015). Despite similar empirical results to the anxiety literature, there are substantially fewer theories to explain the relationship between fatigue and attentional allocation. Given the dynamic nature of the MOT task, this paradigm is a suitable task in which to further explore this relationship.

5.6 Conclusions

The structure of the attentional resource that supports MOT is widely debated. This thesis aimed to distinguish fixed and flexible accounts by developing an unequal attention splitting MOT task. There is evidence that participants can split attention unequally between multiple moving objects which rules out pure fixed models. There is inconclusive evidence regarding the extent to which this ability is fine-grained which is problematic for pure flexible models which would predict any division of attention is theoretically possible. Hybrid models of attention can account for the results presented in this thesis and, therefore, hybrid models specific to MOT must be developed.

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Appendices

Appendix 1. Details of deviations from pre-registrations on the Open Science Framework.

In order to address reviewers' comments, there are several deviations from the initial pre-registration of the experiments presented in this thesis.

<u>All Experiments</u>

1) One reviewer suggested that we conduct a mixture model analysis (based on Zhang and Luck (2008) which provides insight into the proportion of trials on which a participant guessed and the precision of tracking. We therefore did not exclude any data from the analysis reported in the manuscript.

2) In the pre-registration we stated that we would run both frequentist and Bayesian statistics. One reviewer said that the mixture of different analysis was confusing and recommended doing either Bayesian or p-value statistics. Therefore, we do not report Bayesian statistics in the manuscript. Moreover, a reviewer suggested using LME analysis and, therefore, these are used throughout the manuscript.

3) In Experiments 2 - 6, we over-recruit participants due to the method of recruitment via the University of Bristol Experimental Hours System. More timeslots than the required sample size was put on the system due to high drop-out rate and the group testing situation. If a student signs up, they must be given the opportunity to take part in the experiment. This led to over-recruitment in some experiments, but no data analysis was conducted until all date was collected.

<u>Experiment 2</u>

1) In the pre-registration we stated that we would run the analysis on two data sets: 1) All Data; 2) Data excluding trials on which participants did not 'track' the queried target. Participants did not engage with the component of the task which required them to use the left and mouse click for a tracked and untracked target respectively. Therefore, there was no difference between the two data sets. Moreover, following reviewers' comments we now use a different method to determine the proportion of guessing for each participant.

2) In the pre-registration, we state that we would run a one-way ANOVA to explore the effect of target priority on the number of 'tracked' trials. As mentioned above, participants did not engage with this component of the task and, therefore, we could not run this analysis. Instead, we used the mixture modelling analysis to provide insight into the proportion of guessing.

3) In the pre-registration, we state the we would investigate the effect of target priority on response time. Since there was no effect and the reviewers requested us to make the manuscript shorter, this analysis is not reported in the manuscript.

Experiments 3 and 4

1) Experiment 2 (group testing) and Experiment 3 were included in the same pre-registration. Following reviewers' comments, we now report these as two separate Experiments in the manuscript because they used different tasks. Specifically, Experiment 2 (group testing) and Experiment 3 used a trajectory and position tracking task respectively.

2) In response to further reviewers' comments regarding the length of the manuscript, we combined the data from two identical tasks into Experiment 2 in the current manuscript. The only difference was whether participants completed the task alone (Experiment 2: single testing) or in groups (Experiment 2: group testing). The same qualitative pattern of results was observed when each experiment was analysed independently. When experiment was included as a between subject factor there were no reliable differences. Note, under a Bayesian framework combining the data is equivalent to multiplying the Bayes factors from each experiment (assuming the posterior from Experiment N is the prior for Experiment N+2; see Ly, Etz, Marsman, Wagenmakers, 2018).

3) In the pre-registration, we stated that we would test whether there was a cost to unequal attention splitting compared with equal attention splitting using paired samples *t-test*. There was an effect of attention spitting type in the trajectory tracking task but not for the position tracking task. We believe that this is due to the slightly different methodologies in these two tasks. Specifically, in the trajectory tracking task, the unequal splitting conditions had an identity tracking component whereas the equal splitting task did not. In the position tracking task, both attention splitting types had an identity tracking component. Following reviewers' comments regarding the length of the manuscript, the analysis is not included in the manuscript because it is not the main analysis.

4) In the pre-registration, we state the we would investigate the effect of target priority on response time. Since there was no effect and the reviewers requested us to make the manuscript shorter, this analysis is not reported in the manuscript.

Experiments 6 and 7

1) In the pre-registration, we outlined a method for identifying whether participants were guessing the final locations of targets. We now use the Zhang and Luck (2008) method to address this question.

Appendix 2. Details of the eligibility criteria for Experiment 9.

Inclusion Criteria

- Be aged between 18-35 years
- Be in good physical and psychiatric health
- Have English as first language or equivalent level of fluency.
- Have normal or corrected-to-normal vision

Exclusion Criteria

- You consume alcohol within 36 hours of the study session
- You have recently used illicit drugs
- You have high blood pressure (higher than 140/90 mmHg)
- You have high or low heart rate (lower than 50 or higher than 90 beats per minute)
- You are pregnant or breastfeeding
- Your Body mass index (BMI) is less than 17 kg/m^2 or greater than 30 kg/m^2
- You have significant current or past medical or psychiatric illness
- You have a personal or strong family history of mood disorder, including panic disorder
- You have ongoing physical illness or abnormality (e.g., history of cardiac or respiratory problems, including asthma)
- You have personal history of migraine
- You are not registered with a general practitioner (GP)
- You drink more than 35 alcoholic units*/week for females and 50 units*/week for males
- You drink more than eight caffeinated drinks per day
- You have a personal history of alcoholism or drug dependence
- You are currently using medication use (except local treatment, aspirin or paracetamol); within past 8 weeks if study session
- You have impaired or uncorrected vision
- You have impaired or uncorrected hearing

* One unit equals one 25ml single measure of spirit (ABV 40%), or a third of a pint of beer (ABV 5-6%) or half a standard (175ml) glass of red wine (ABV 12%).

Appendix 3. Consolidation Standards of Reporting Trials (CONSORT) Flow Diagram